Input Data

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In This Session …

- Discuss input data required for 3D frac models
- Introduce the complete stress equation as implemented in GOHFER
- Break apart the elements of the stress equation
  - Poisson's Ratio and Young's Modulus
  - Net Effective Stress
    - Pore Pressure, Overburden Pressure, Biot's Constant
  - External Stress Boundary Conditions
- Height Containment Mechanisms other than Stress Contrast

Types of Input Data

- Control of Stress Profile
  - Poisson's Ratio
  - Young's Modulus
  - Stress and Strain Offsets
  - Pore Pressure
  - Biot's Alpha
  - Depth
  - OB Gradient
- Control of Fracture Growth
  - Stress Profile
  - Process Zone Stress

Other input data relating to fluid loss and efficiency, fluid and solid transport, and post frac production will be discussed later.

Definition of Stress and Pressure

- Stress and pressure are both terms for the magnitude of an applied force per unit area (lb_f/in^2, Pa, bar, atm, kg/m^2, etc.)
- the term "pressure" is applied to fluids
  - Pressure acts equally in all directions
  - Pressure has magnitude only
- The term "stress" is applied to solids
  - Stress has direction and magnitude
  - Stress is considered to be a vector or tensor quantity
  - Stress is not isotropic
  - Positive stresses lead to compression and negative stresses to extension

In Situ Earth Stresses

- Stresses caused by overburden weight
  - Vertical to horizontal transform through confined compaction
- Stresses caused by tectonic movements
- Stresses caused by creep-flow and plasticity
- Effects of pore pressure and its variation
- Stresses caused by diagenesis

Obtain elastic properties from core and logs

Infer all other influences from field measurements

GOHFER's Complete Stress Equation

$$P_c = \frac{\nu}{(1-\nu)}\left[P_{ob} - \alpha_v P_p\right] + \alpha_h P_p + \varepsilon_x E + \sigma_t$$

- P_c = closure pressure, psi
- ν = Poisson's Ratio
- P_{ob} = Overburden Pressure
- α_v = vertical Biot's poroelastic constant
- α_h = horizontal Biot's poroelastic constant
- P_p = Pore Pressure
- ε_x = regional horizontal strain, microstrains
- E = Young's Modulus, million psi
- σ_t = regional horizontal tectonic stress

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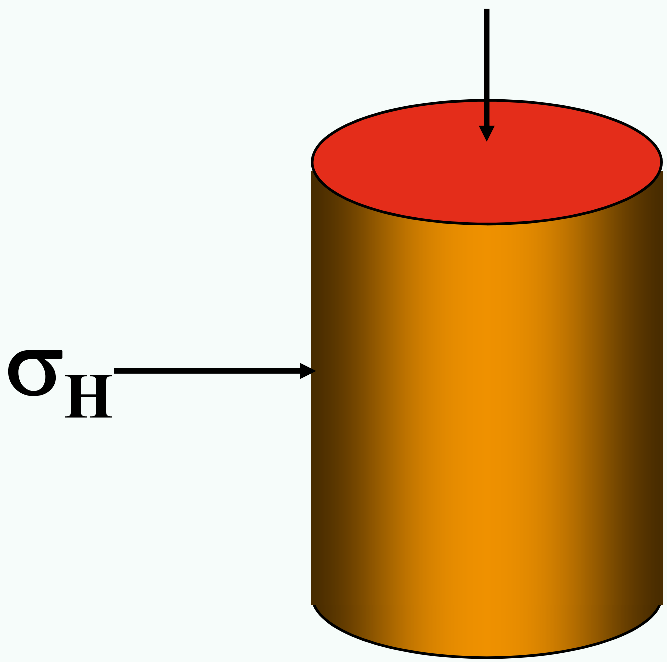
Uniaxial Strain: Deformation in One Direction

$$\sigma_v = P_{OB} - \alpha P_P$$



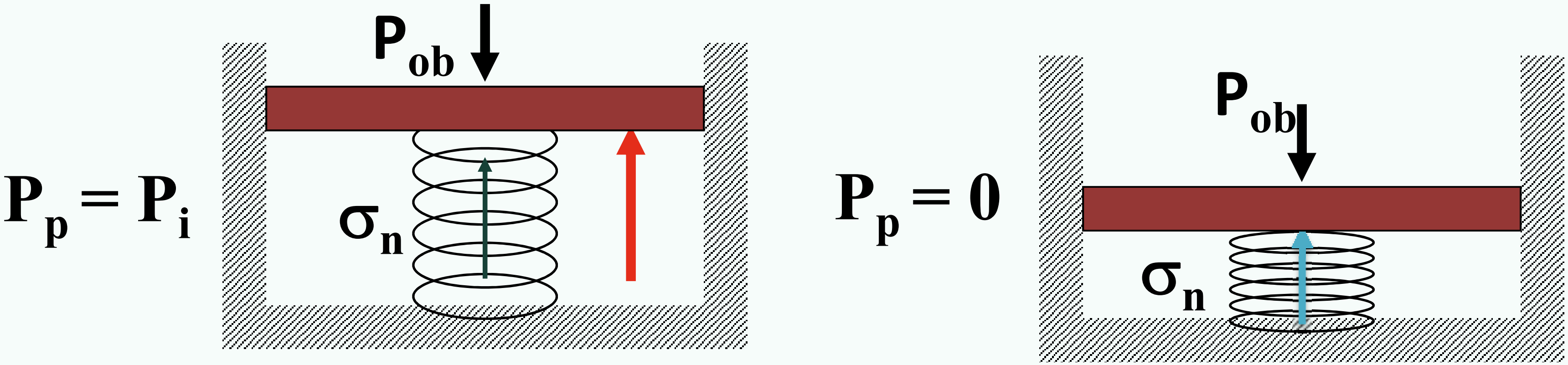
Horizontal stress required to assure no lateral strain

$$\sigma_H = \left(P_{OB} - \alpha P_P\right)\frac{\upsilon}{\left(1-\upsilon\right)}$$

Overburden Pressure

- P_{ob} is the externally applied load
- In GOHFER expressed by:
  - $D_{tv}\gamma_{ob}$
  - Where
    - γ_{ob} is the overburden stress gradient, psi/ft
    - D_{tv} is the true vertical depth, feet

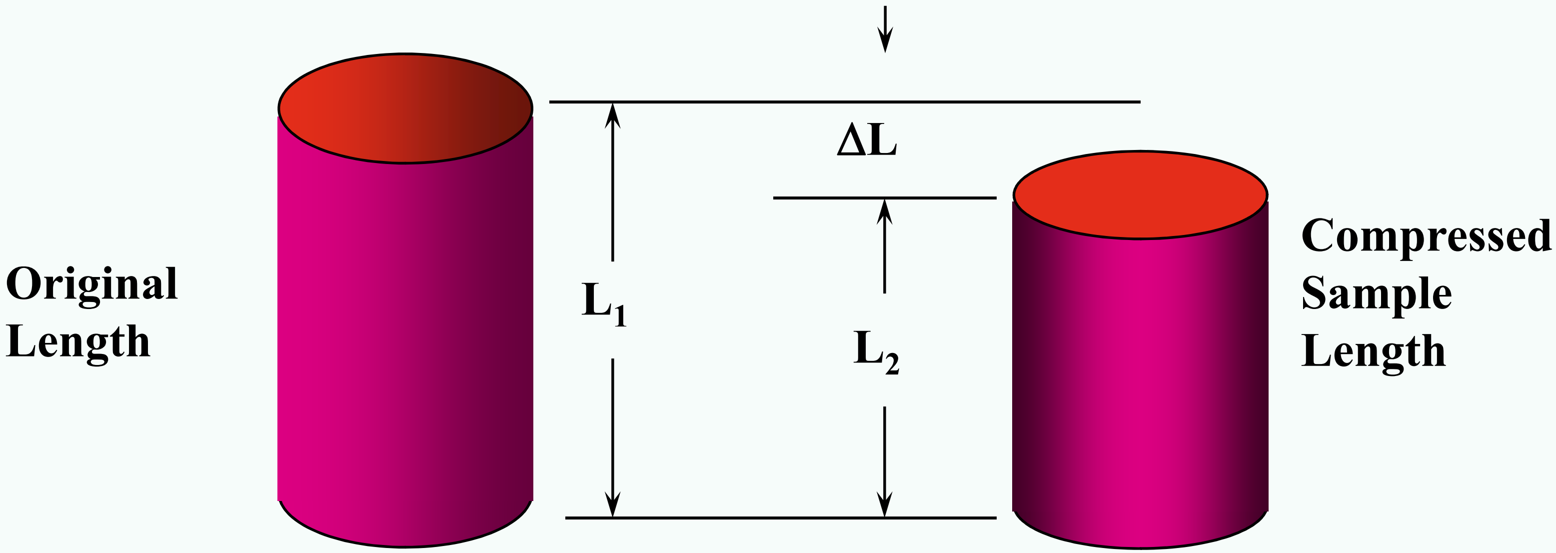
Net Stress Causes Rock Deformation



- *Total Stress Remains Constant*
- *As pore pressure declines, net stress increases*
- $\sigma_n = P_{ob} - \alpha P_p$

Definition of Strain

$$\text{Strain} = \frac{\text{Change in Length}}{\text{Original Length}} \qquad \varepsilon = \frac{L_2 - L_1}{L_1} = \frac{\Delta L}{L}$$



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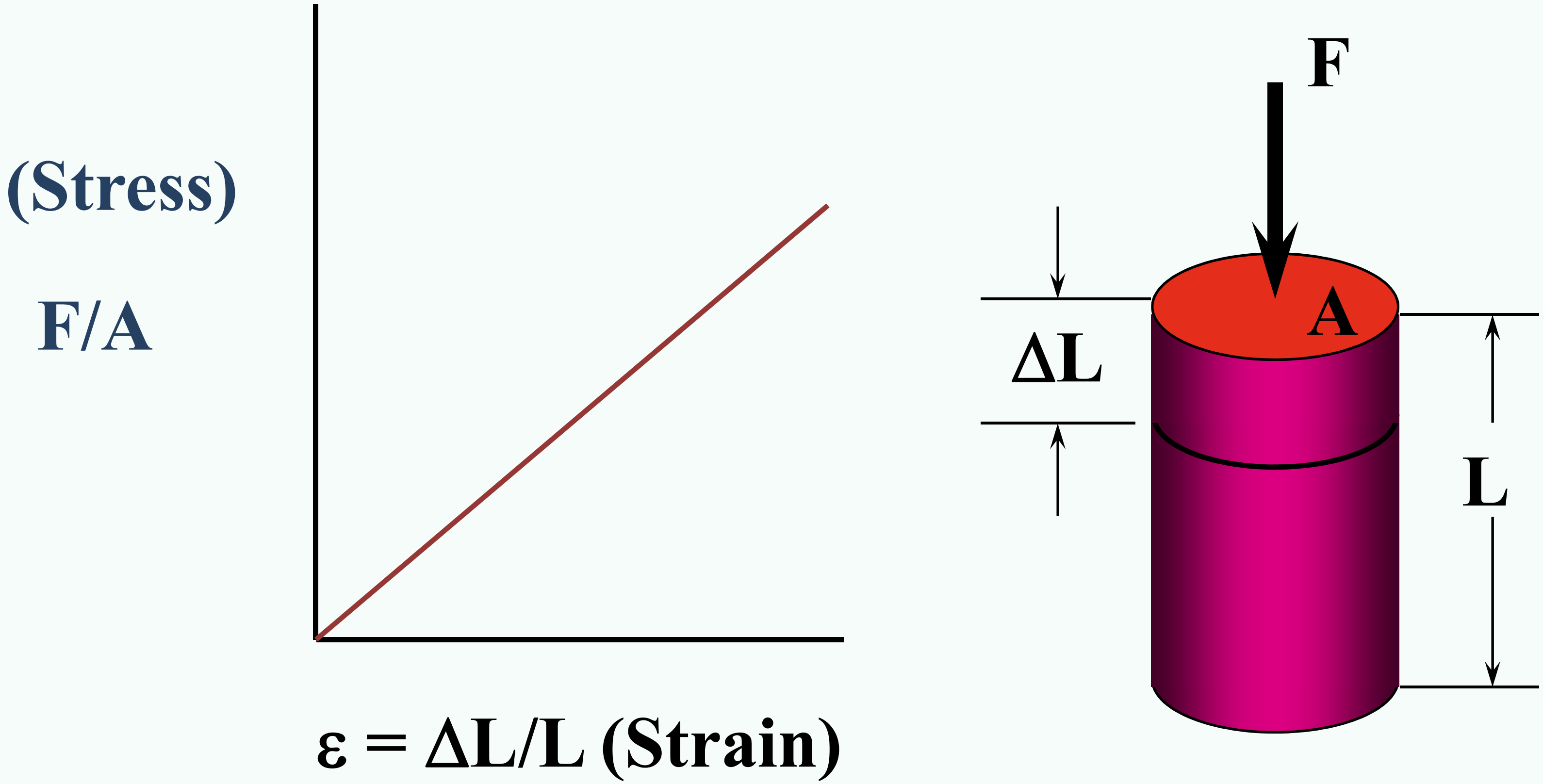
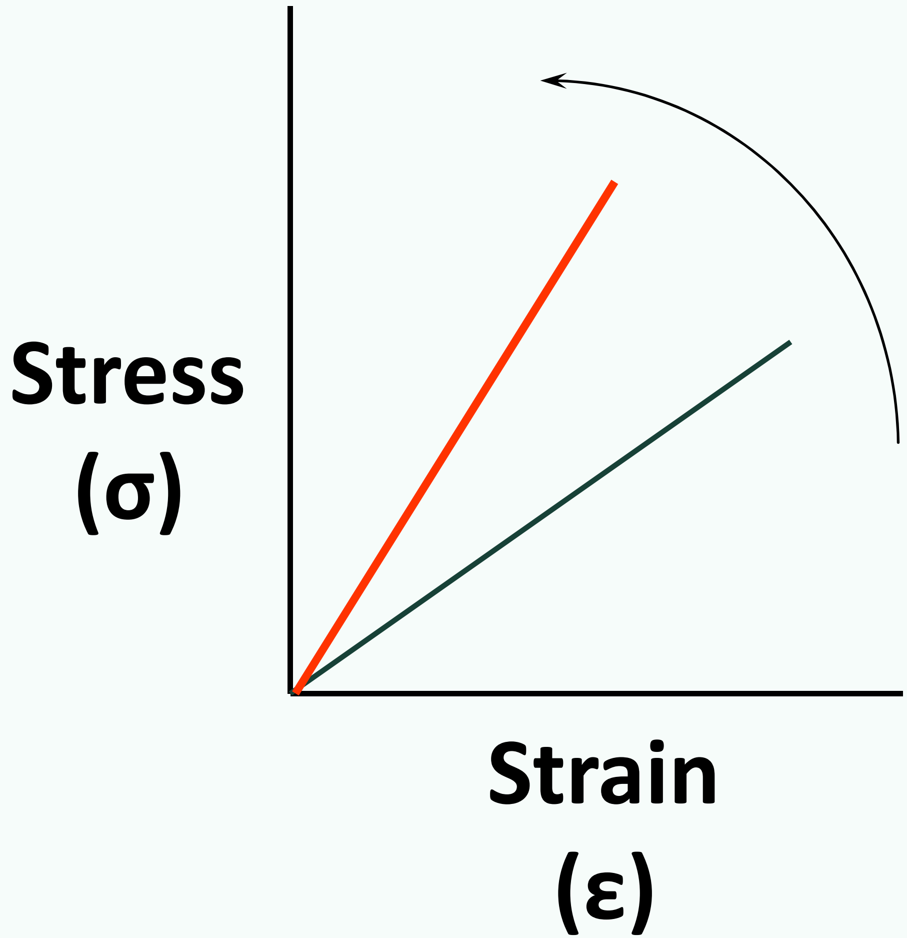
Stress/Strain Relationship



Stress/Strain Slope – Rock Stiffness

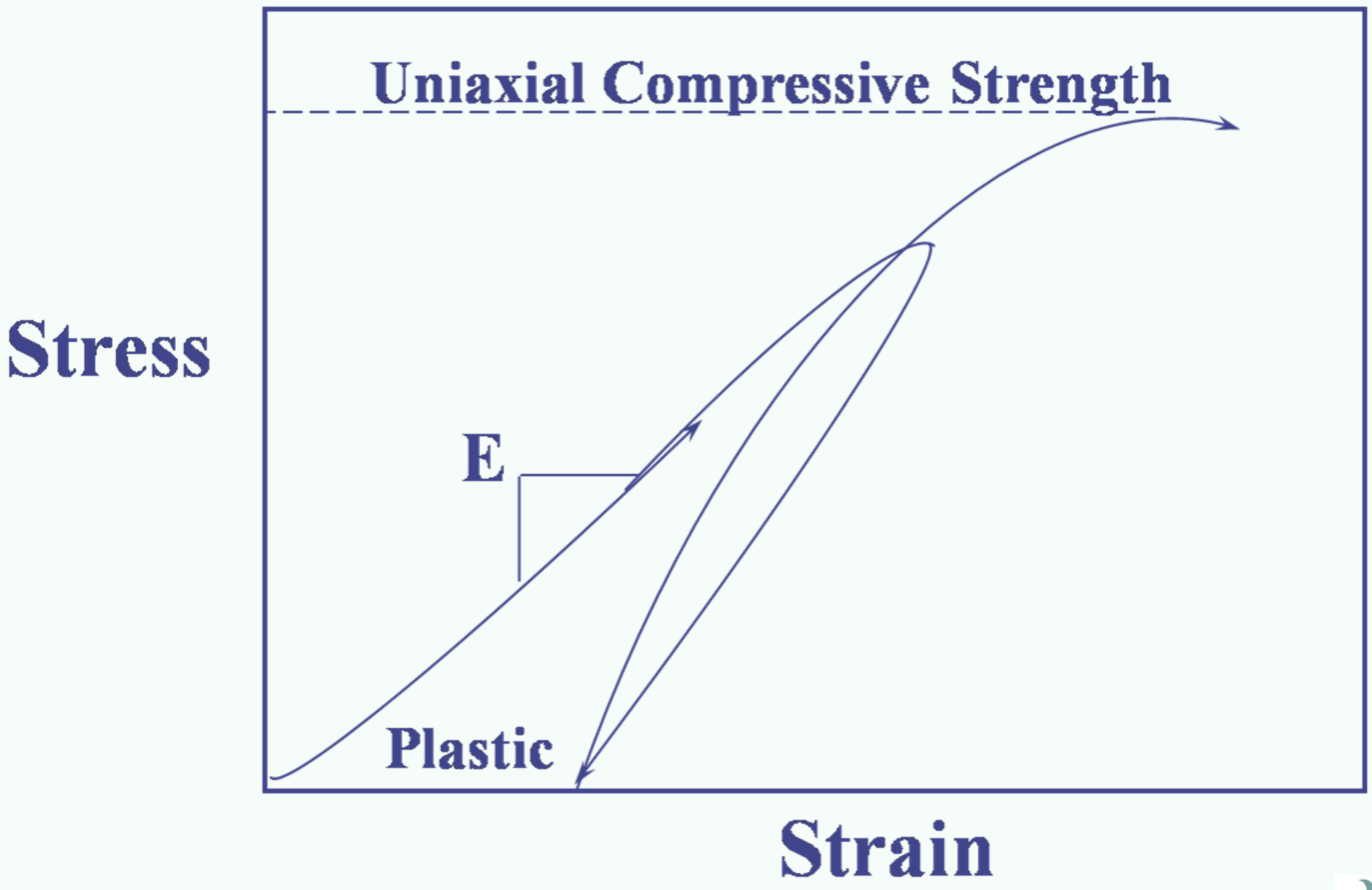


- Young's Modulus:

  $E=\sigma/\varepsilon$

- Higher Slope Indicates Stiffer Material

Young's Modulus is Not a Constant & Deformation is Non-Linear



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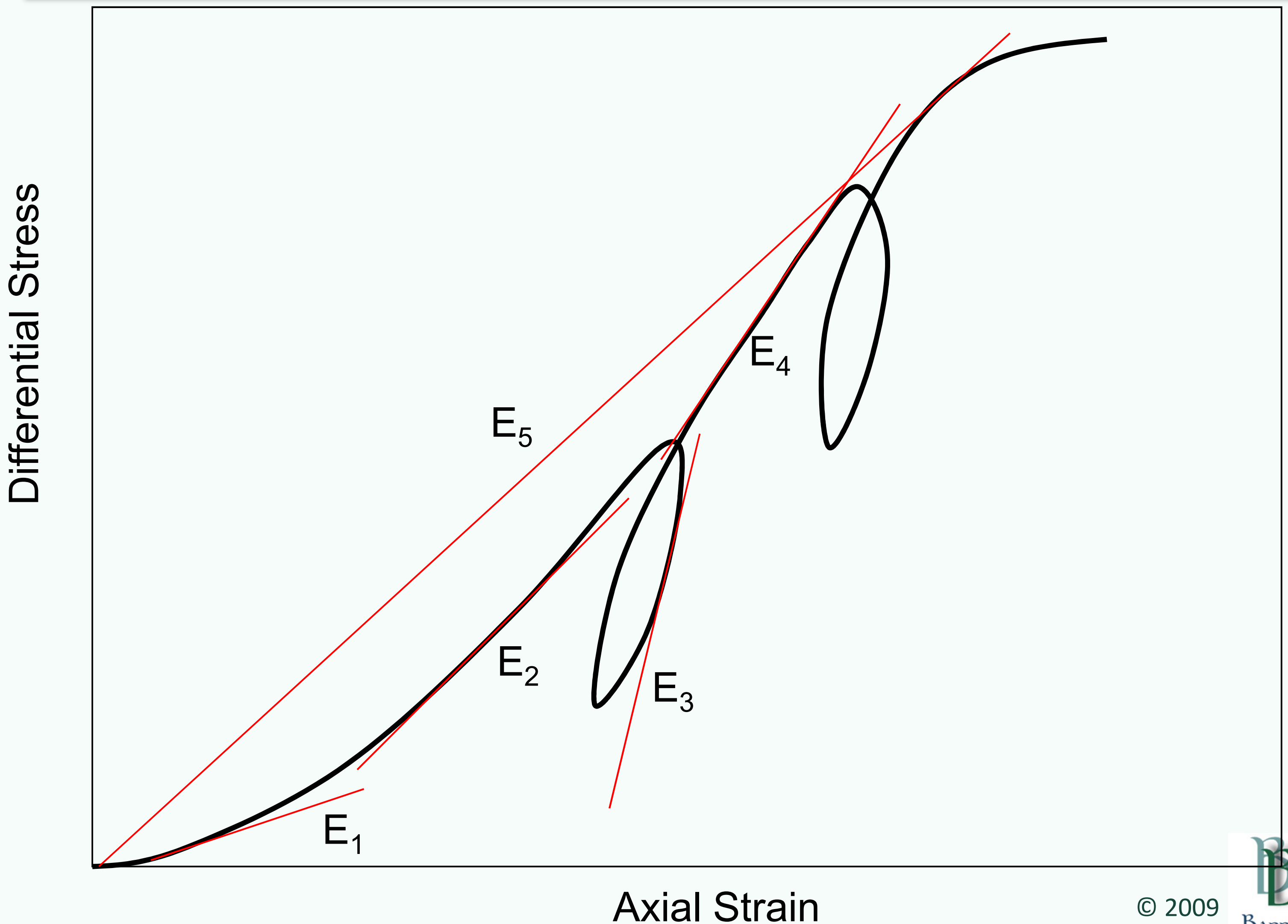
Core Alteration During Coring and Handling

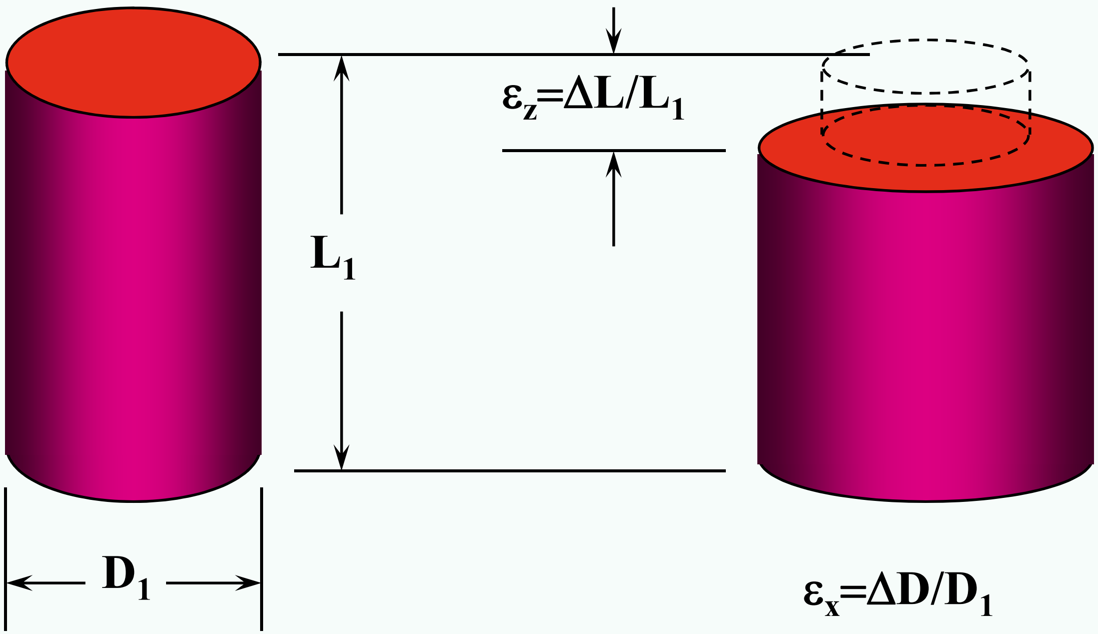
- Removal of overburden stress while coring:
  - Core disking and fracturing
- Removal of confining stress during core recovery:
  - Expulsion of trapped pore pressure
  - Generation of microfractures
  - Anelastic strain (differential expansion) of core
- Thermal contraction
- Dessication and oxidation
- Stress cycling and non-representative stress states
- Improper restoration of saturation

Modulus Depends on Conditions of Measurement



Definition of Poisson's Ratio

Poisson's Ratio = $\nu = \varepsilon_x / \varepsilon_z$



$$\boxed{0 < \nu < 0.5}$$

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Measurement of Dynamic and Static Elastic Properties

- Dynamic modulus must be converted to static modulus
  - Static Modulus: large amplitude at low (zero) frequency (load frame tests)
  - Dynamic Modulus: small amplitude at high frequency (acoustic waves)
- Which stress state best defines the right conditions to measure modulus?
  - Results affected by strain rate, saturations, temperature, frequency, history, time, and many other factors

Modeling of P_p: Pore Pressure

Incorrect Pressure Distribution → Incorrect total stress profile → Incorrect Fracture Geometry

- Usual ‘apparent’ gradient gives pressure only at datum
- In the GOHFER total stress equation
  - expressed in more complex form
  - reflects change in pressure (and stress) across depth interval to be stimulated

$$P_p = \left(D_{tv}\gamma_p + P_{off}\right)$$

D_{tv} = true vertical depth (feet)
γ_p = pore fluid gradient, psi/ft
P_{off} = pore pressure offset, psi

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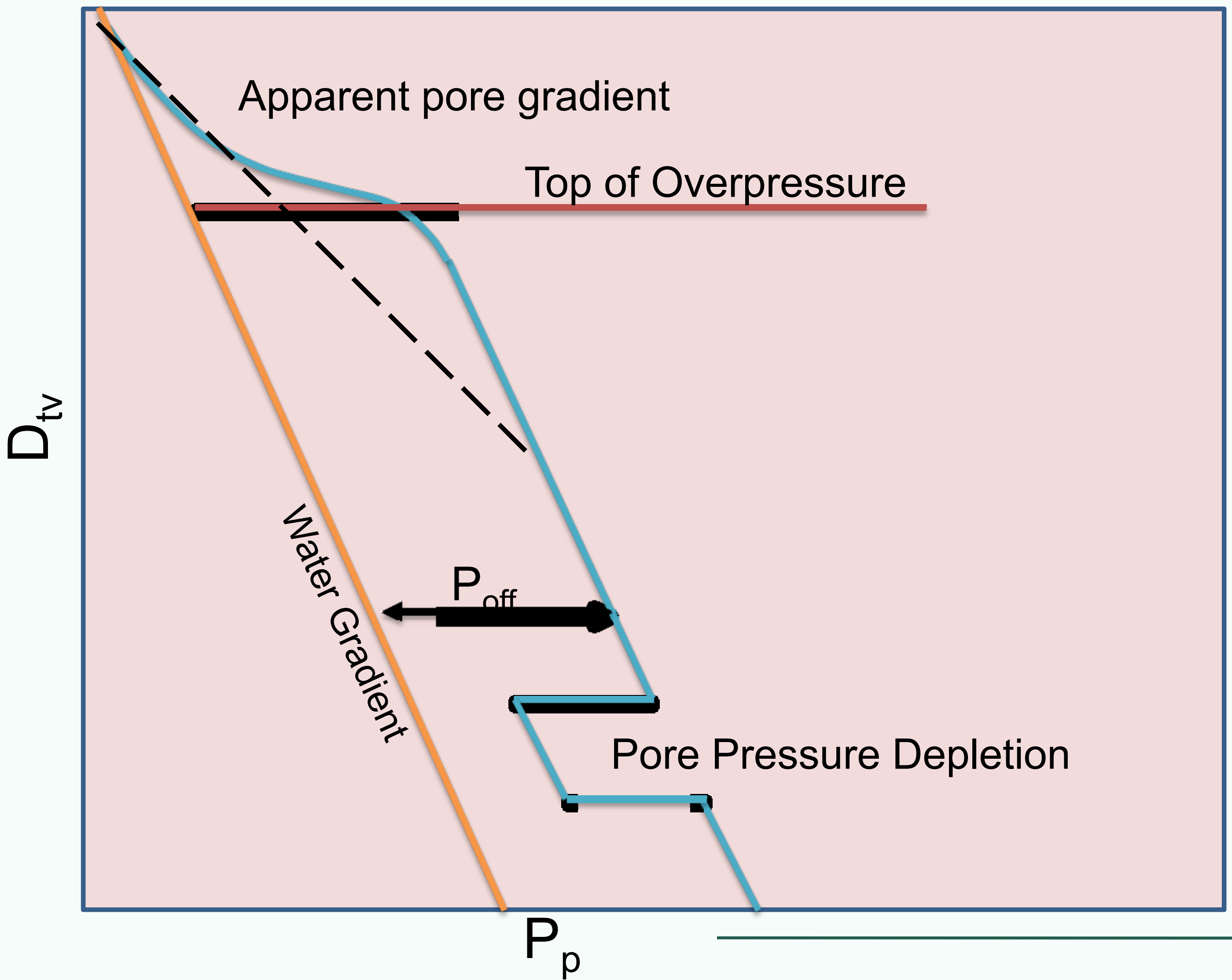
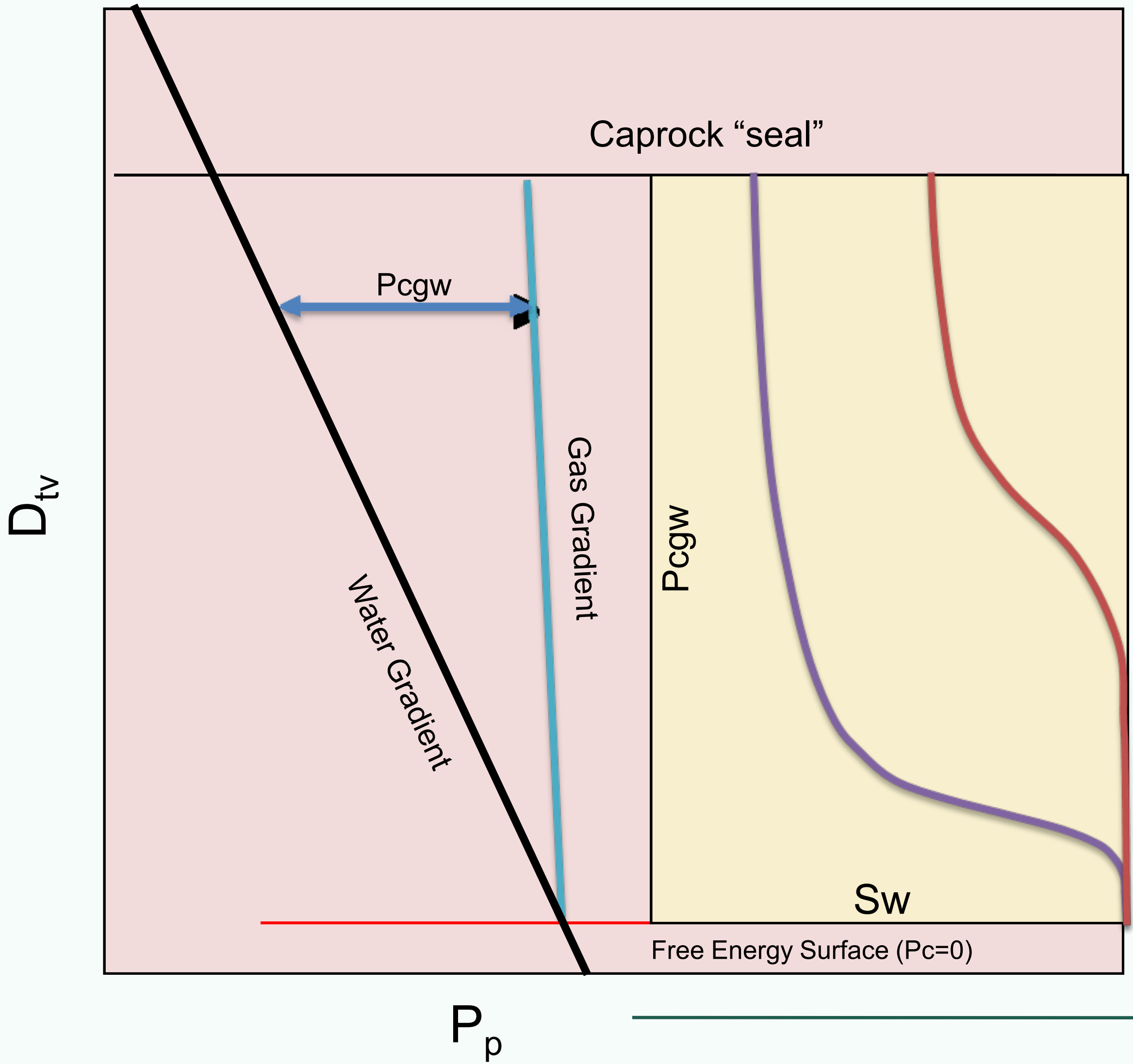
Variable Pore Pressure Offset
Geo Pressured Environment



Variable Pore Pressure Offset

Gravity-Capillary Pressure System



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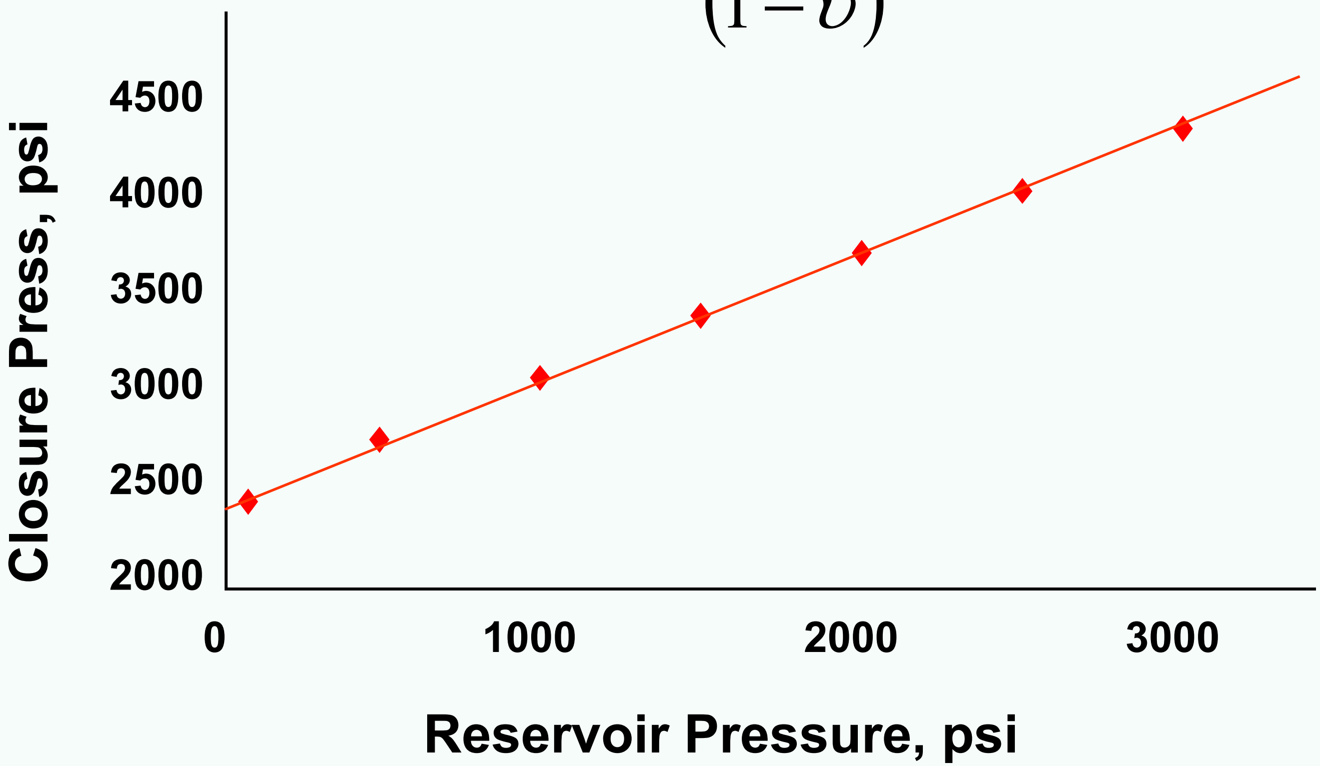
Effect of Pore Pressure on Stress

- Pore fluid supports part of the total stress
- Pore pressure depletion increases net stress and leads to compaction
- Pore pressure depletion decreases total (fracture closure) stress
- Fractures tend to grow into region of lowest pore pressure

Pore Pressure Variations Induce Closure Stress Contrasts

- Closure Pressure (P_c) is affected by Pore Pressure (P_p):

$$P_c = \frac{\upsilon}{(1-\upsilon)}\left(P_{ob} - \alpha P_p\right) + P_p + \sigma_x$$



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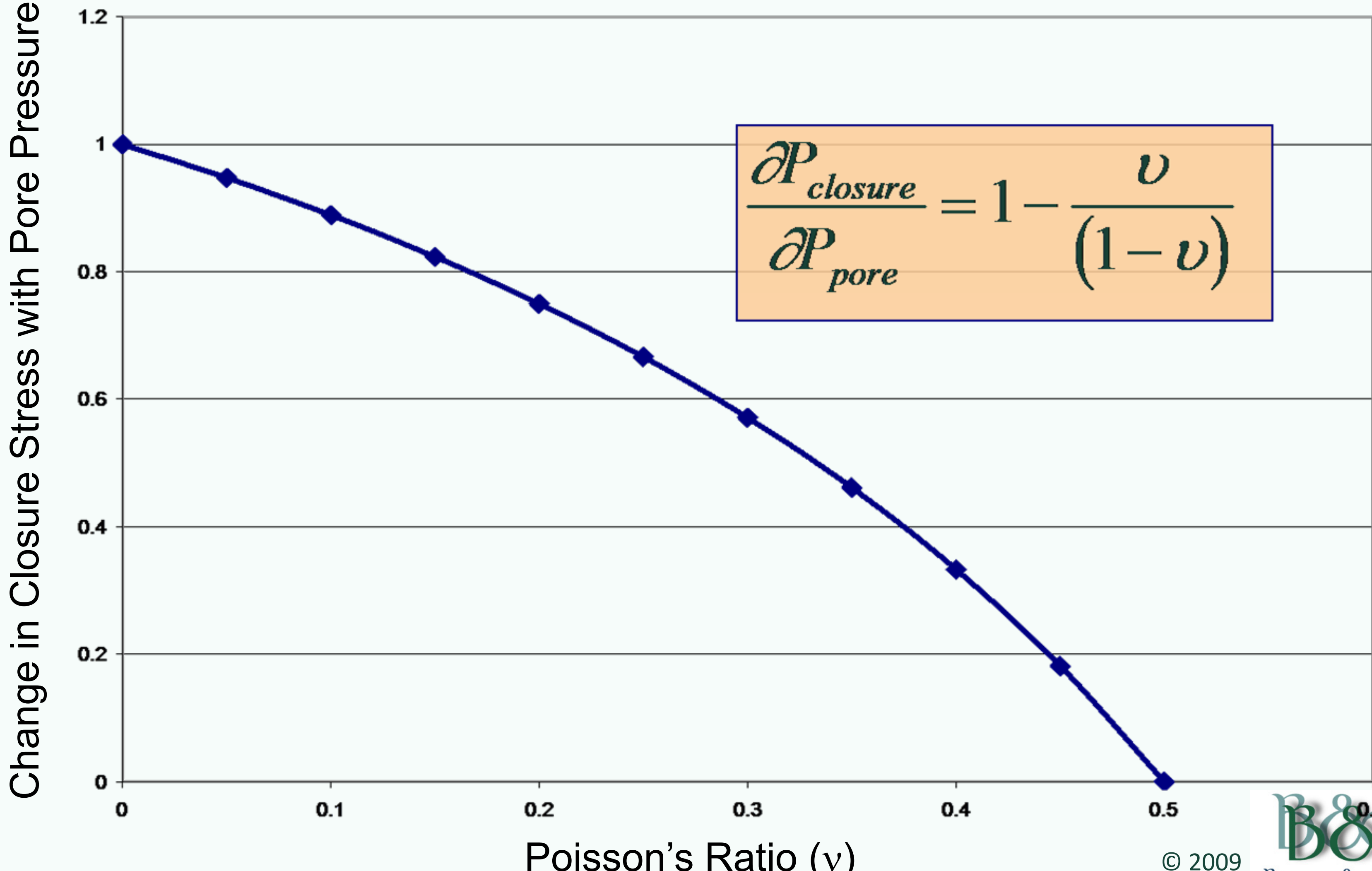
Closure Stress Change Related to Pressure Depletion and PR



$$\frac{\partial P_{closure}}{\partial P_{pore}} = 1 - \frac{\upsilon}{(1-\upsilon)}$$

Reservoir Pressure Gradients

- Fractures grow into areas of lower closure stress or pressure
  - vertical fracs grow upward in uniform rock
- Lateral pressure gradients have the same effect as vertical gradients
- Drilling and fracing in a pressure gradient can lead to asymmetric fracture growth

What We Have So Far

- So far we have transformed this:

$$\left[P_{ob} - \alpha_v P_p\right] + \alpha_h P_p$$

- to

$$\left[D_{tv}\gamma_{ob} - \alpha_v\left(D_{tv}\gamma_p + P_{off}\right)\right] + \alpha_h\left(D_{tv}\gamma_p + P_{off}\right)$$

So what about that α??

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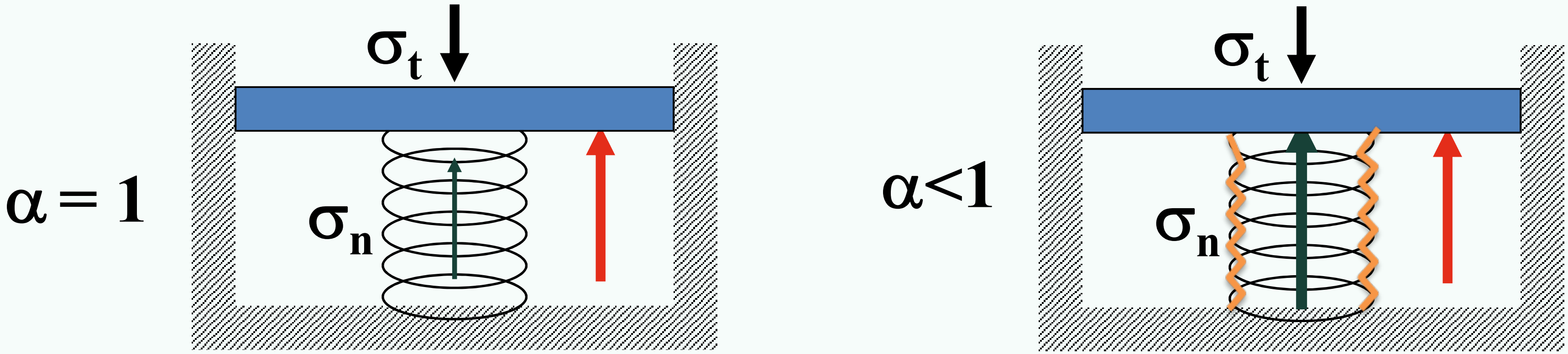
Biot's Poroelastic Constant

- Internal fluid pressure is not transmitted perfectly to the rock matrix
- Correction factor applied
  - Biot's poroelastic constant (α)
- So net effective stress is:
  - $\sigma_n = P_{ob} - \alpha P_p$
  - *Which should make one part of the GOHFER equation recognizable as the net effective stress.*

Biot's Constant & Its Effects on Stress

- Biot's poroelastic constant (α) is *the efficiency with which internal pore pressure offsets the externally applied vertical total stress*
- as α declines, net (intergranular) stress increases and pore pressure variations have less impact on net stress



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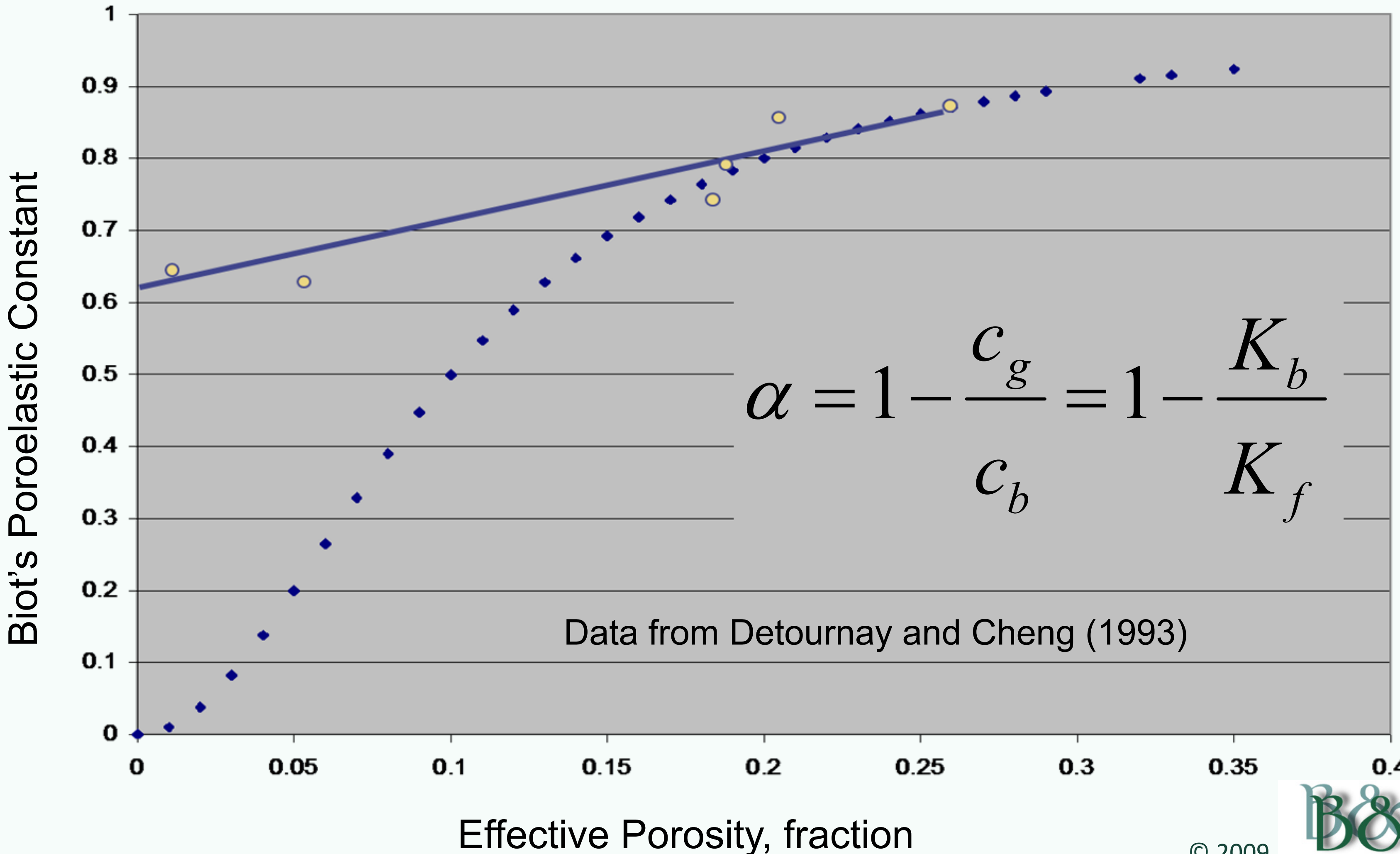
Possible Correlations for α



$$\alpha = 1 - \frac{c_g}{c_b} = 1 - \frac{K_b}{K_f}$$

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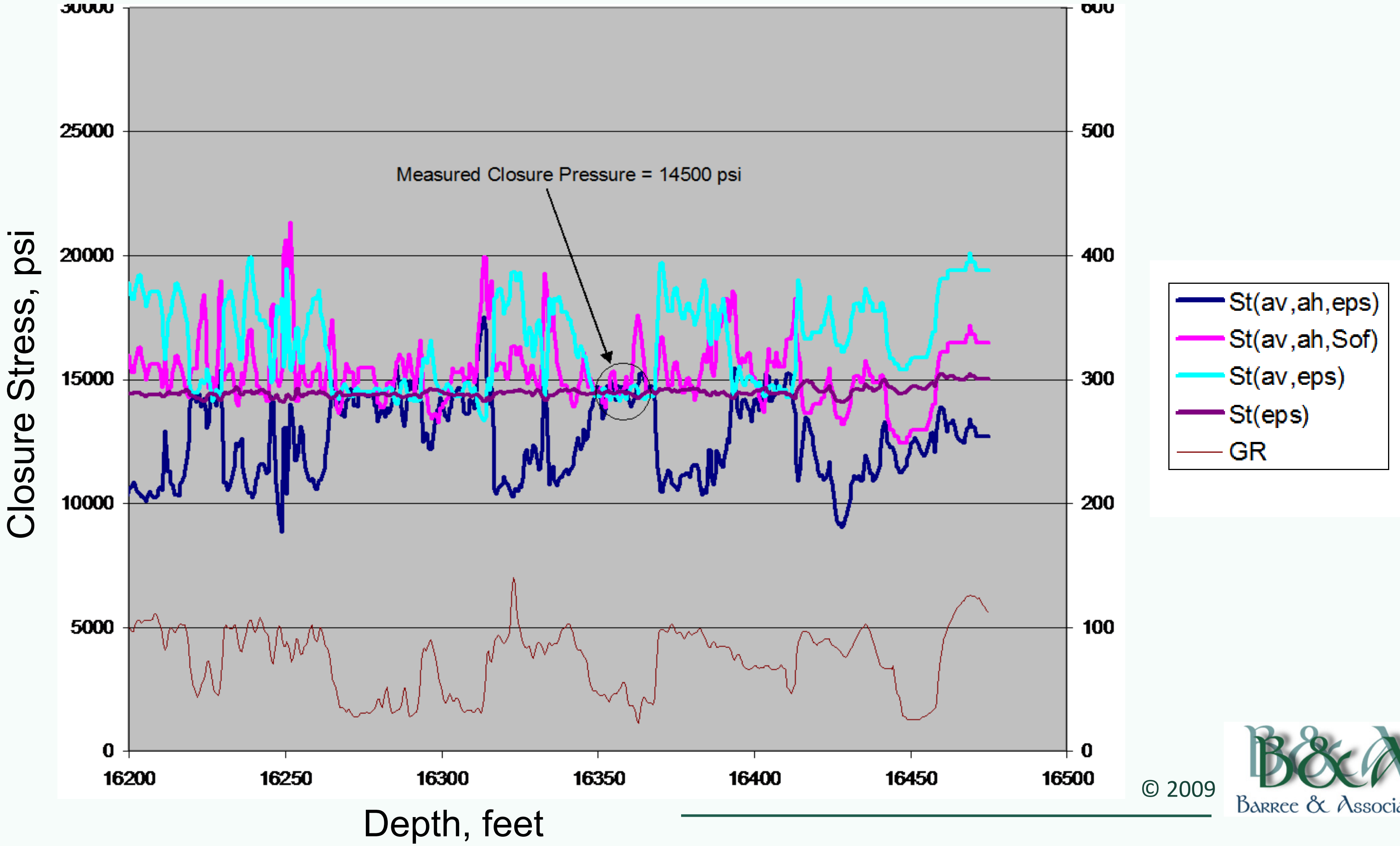
Assumptions in Stress Calculations

$$P_c = \frac{\nu}{(1-\nu)}\left[P_{ob} - \alpha_v P_p\right] + \alpha_h P_p + \varepsilon_x E + \sigma_t$$

To calculate P_c assumptions must obviously be made about α – possibilities include:

- $\alpha_v = \alpha_h$ f(PHIE), constant strain offset
- $\alpha_v = \alpha_h$ f(PHIE), constant stress offset
- α_v variable, α_h=1, strain offset
- $\alpha_v = \alpha_h$=1, strain offset

Resulting Stress Profiles



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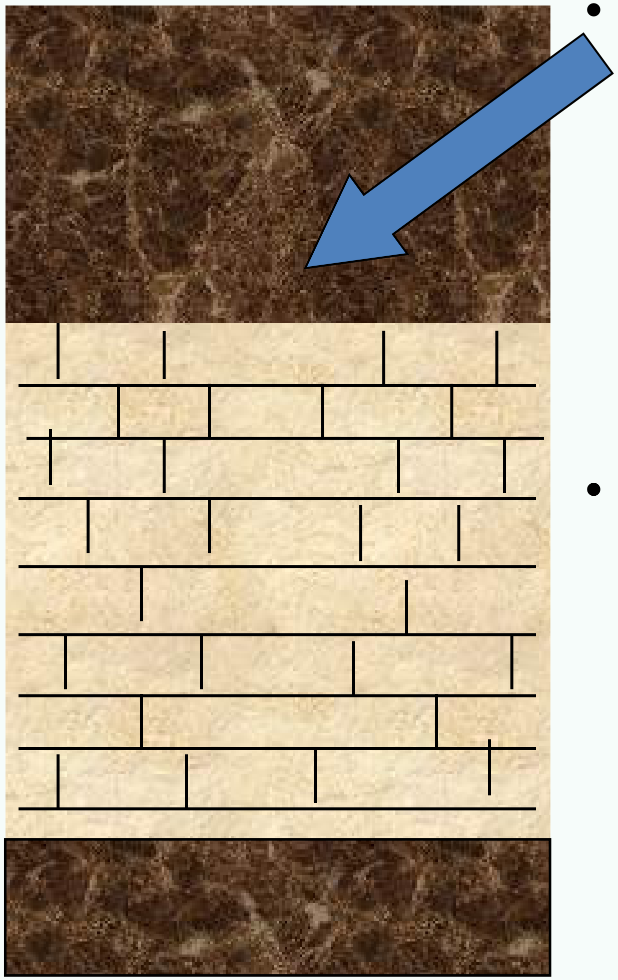
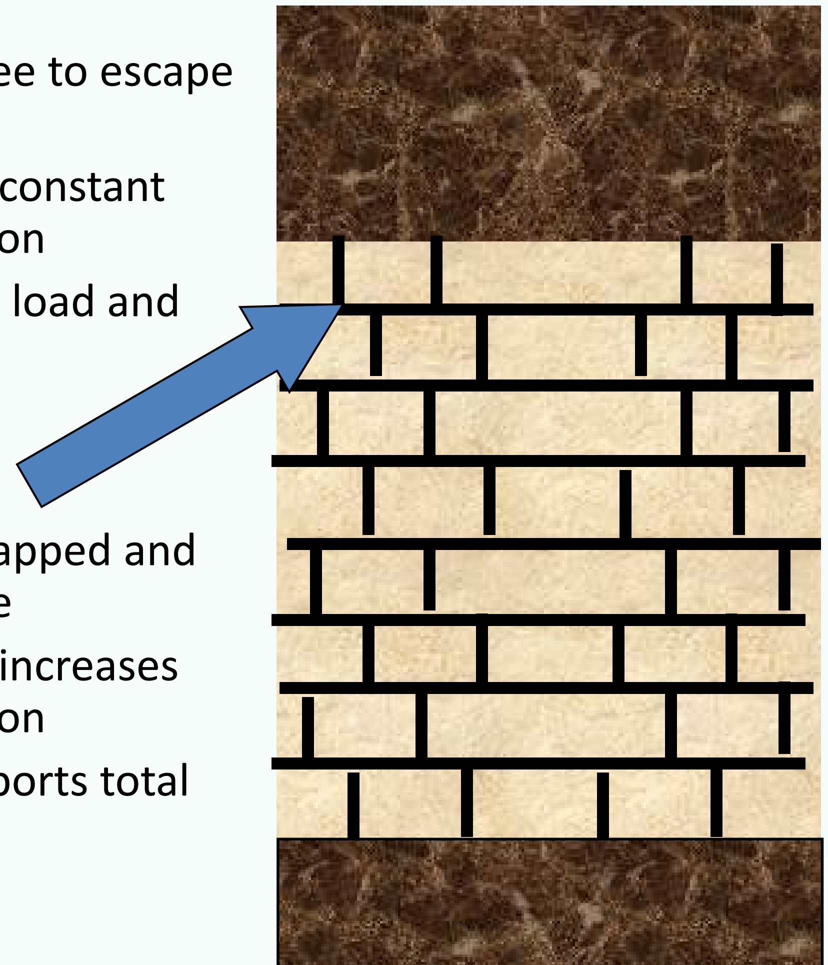
Drained vs. Undrained Poisson's Ratio and Young's Modulus in Coals



- Drained Test:
  - Pore fluid is free to escape or compress
  - Pore pressure constant with compaction
  - Cleats support load and may shear
  - $\nu=0.35$
- Undrained Test:
  - Pore fluid is trapped and incompressible
  - Pore pressure increases with compaction
  - Pore fluid supports total stress
  - $\nu=0.5$

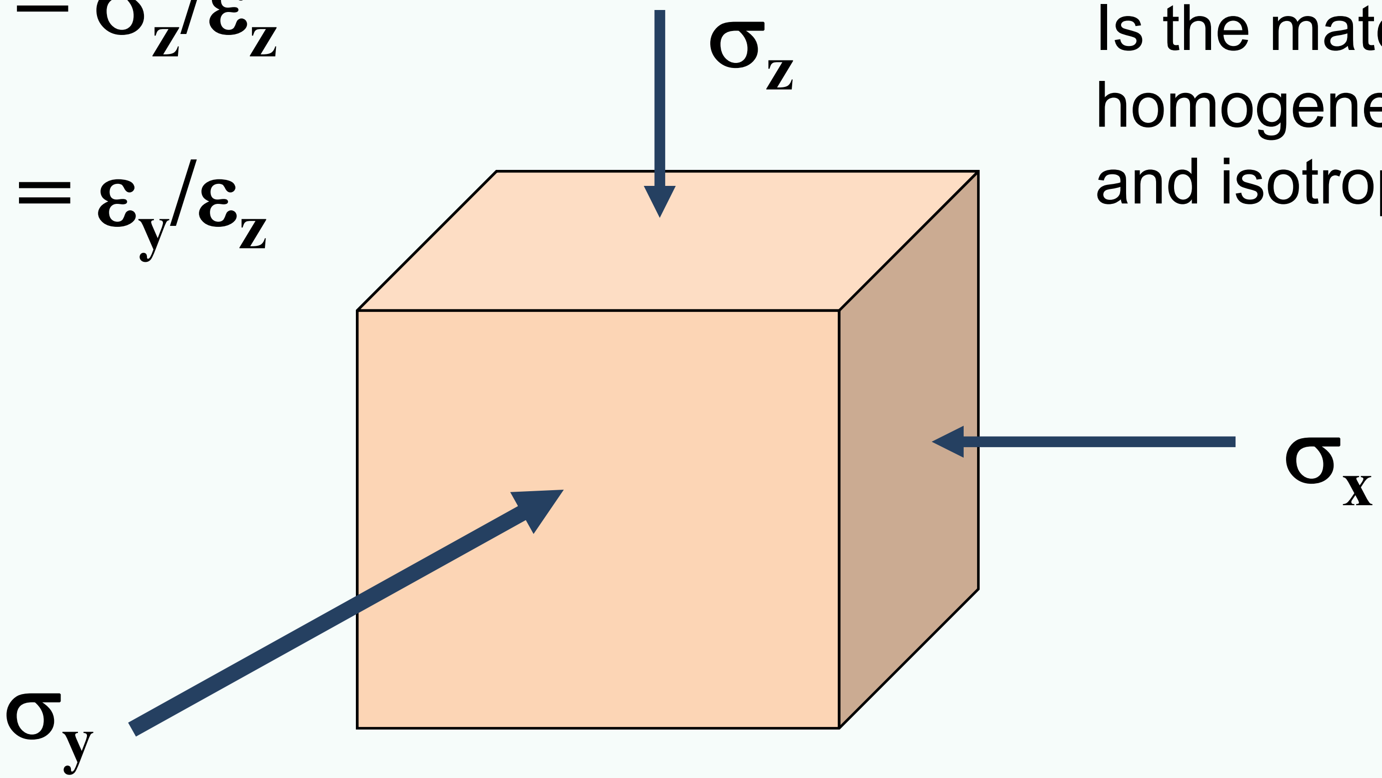


Triaxial Loading:

Defined by Three Principal Stresses

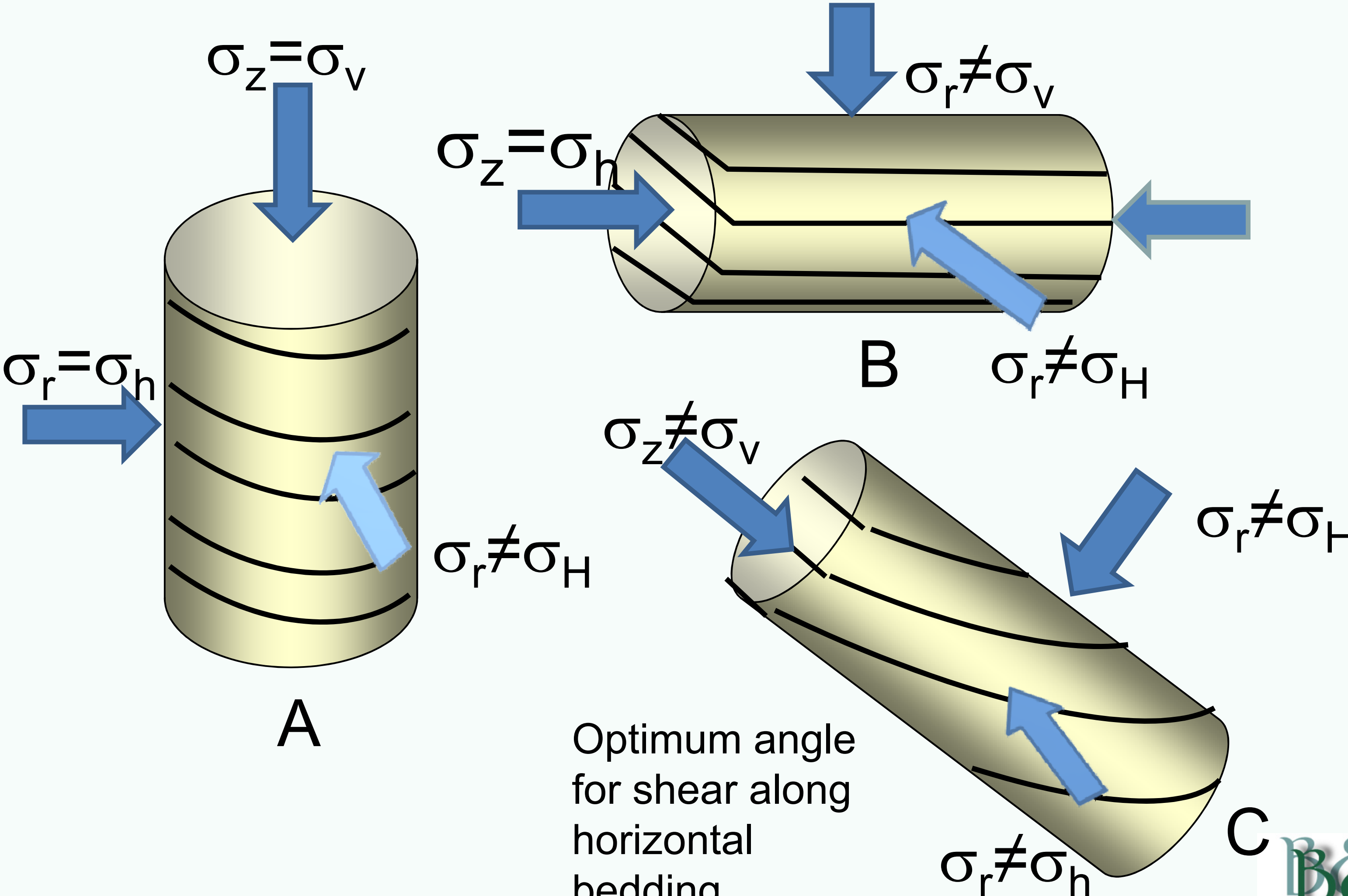
$$E = \sigma_z/\varepsilon_z$$

$$\nu = \varepsilon_y/\varepsilon_z$$



Is the material homogeneous and isotropic?

Oriented Anisotropic Core Data: What does it mean?



Optimum angle for shear along horizontal bedding

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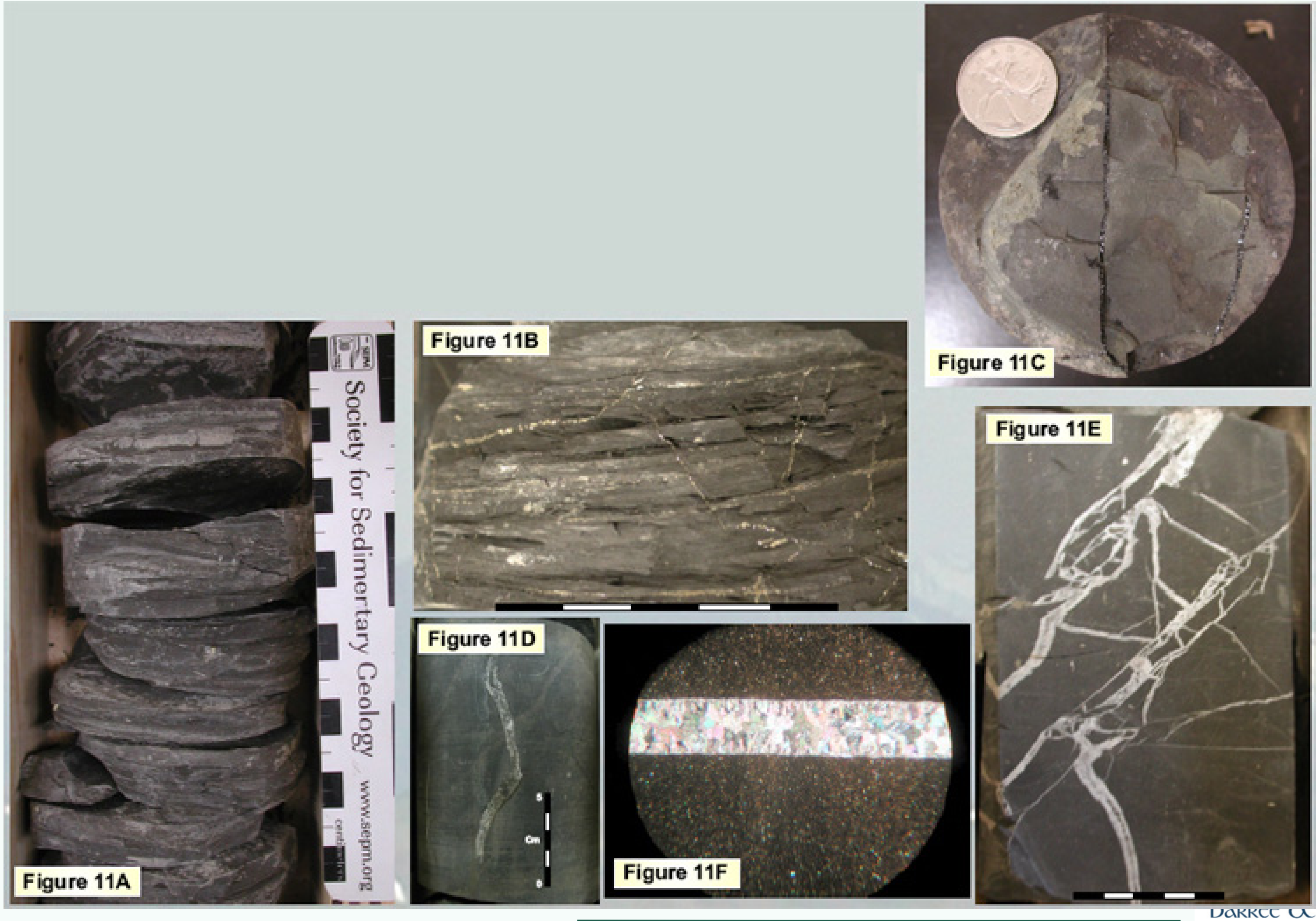
Fractures, Laminations, and Sample Scale Effects in Shale



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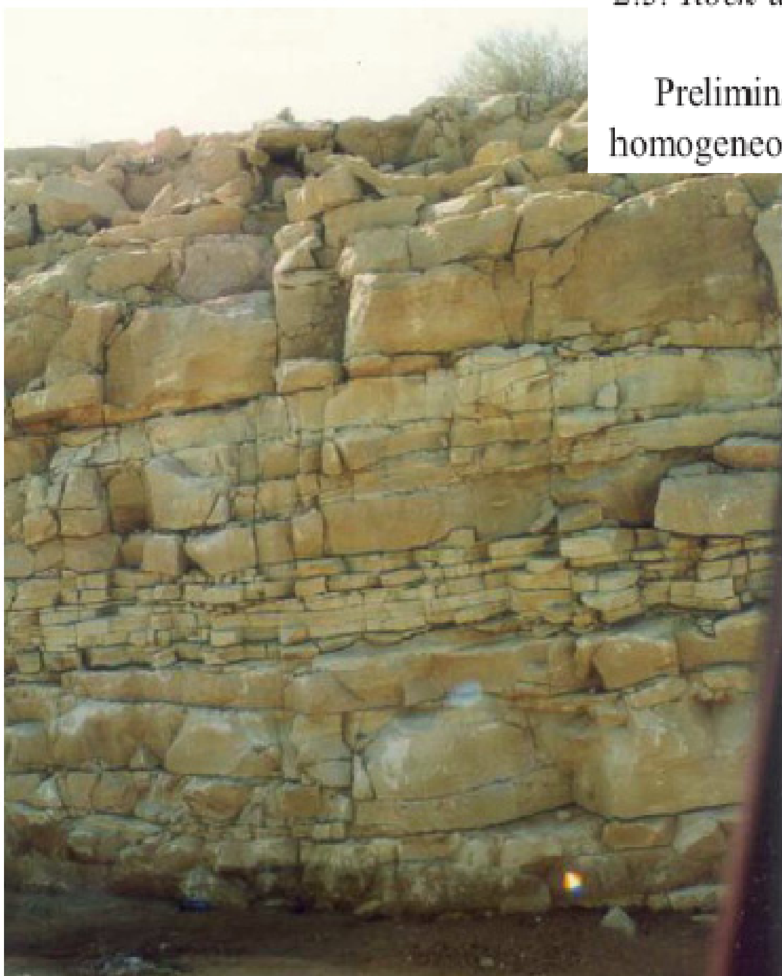
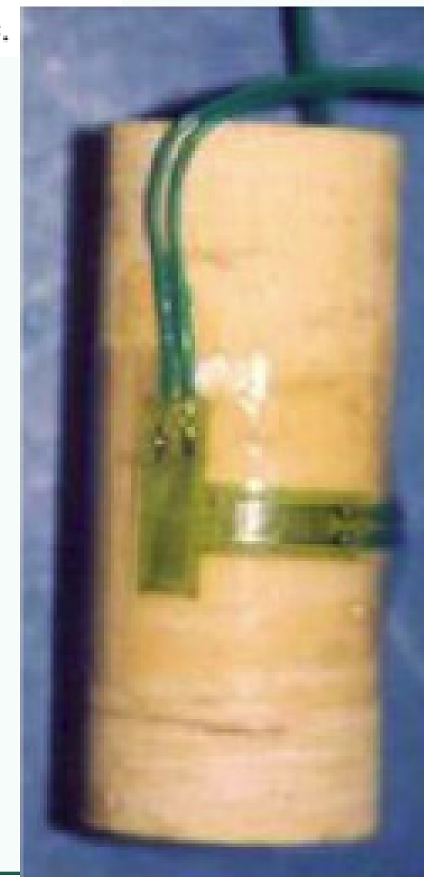
Homogeneity and Anisotropy: What are we measuring?

2.3. Rock description

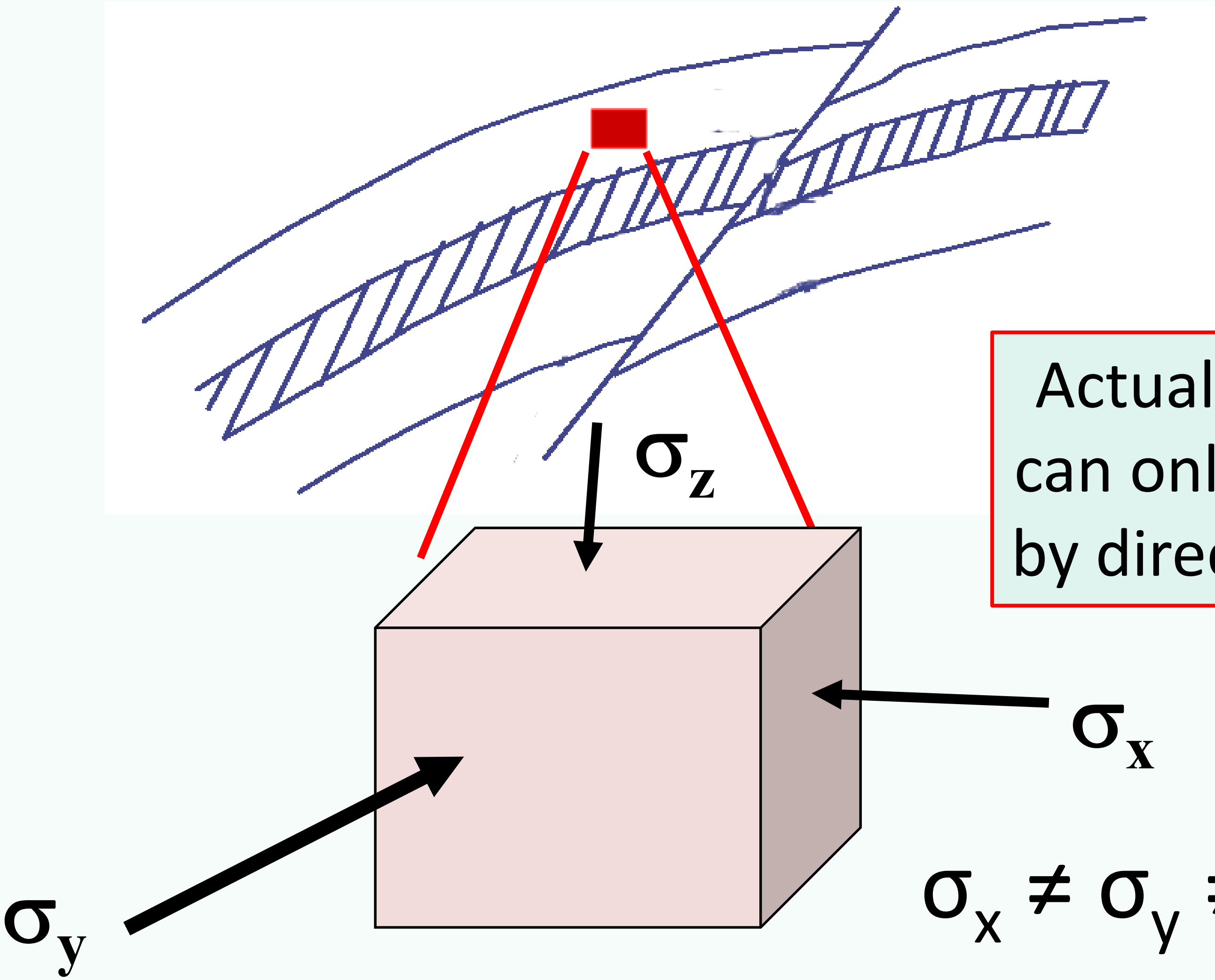
Preliminary studies showed that this rock is a very homogeneous, beige-colored, muddy limestone.





What Are the Mechanical Properties of This?

More Complex Realistic In-Situ Stress States



Actual in-situ stresses can only be determined by direct measurement.

$$\sigma_x \neq \sigma_y \neq \sigma_z$$

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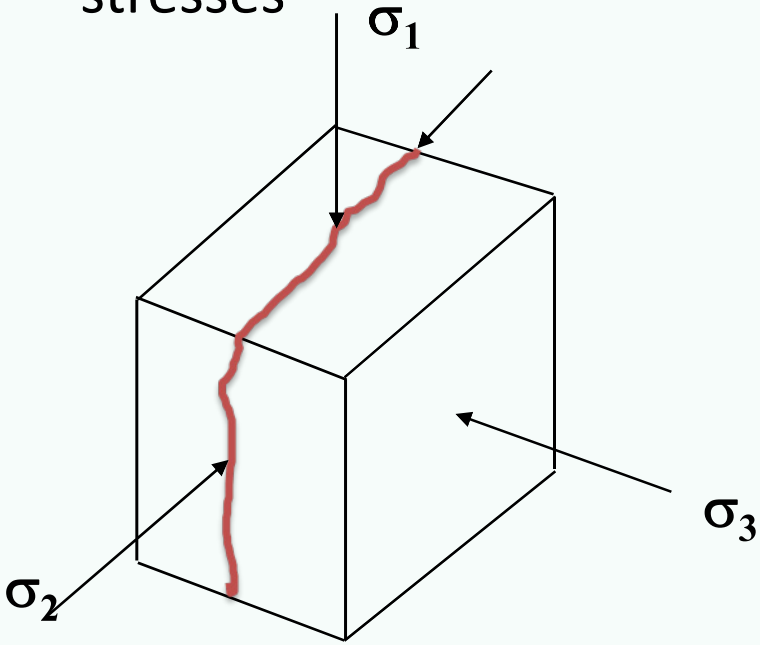
In-Situ Stress Field Controls Fracture Orientation

- Fracture orientation determined by relationship of principal stresses



- Stress distribution controls fracture orientation, height containment, treating pressure magnitude, and change in treating pressure during
- Orientation of induced fractures controlled primarily by the stress difference between the 3 principal stresses
- the major displacement (opening of fracture width) occurs in the direction of the minimum principal stress

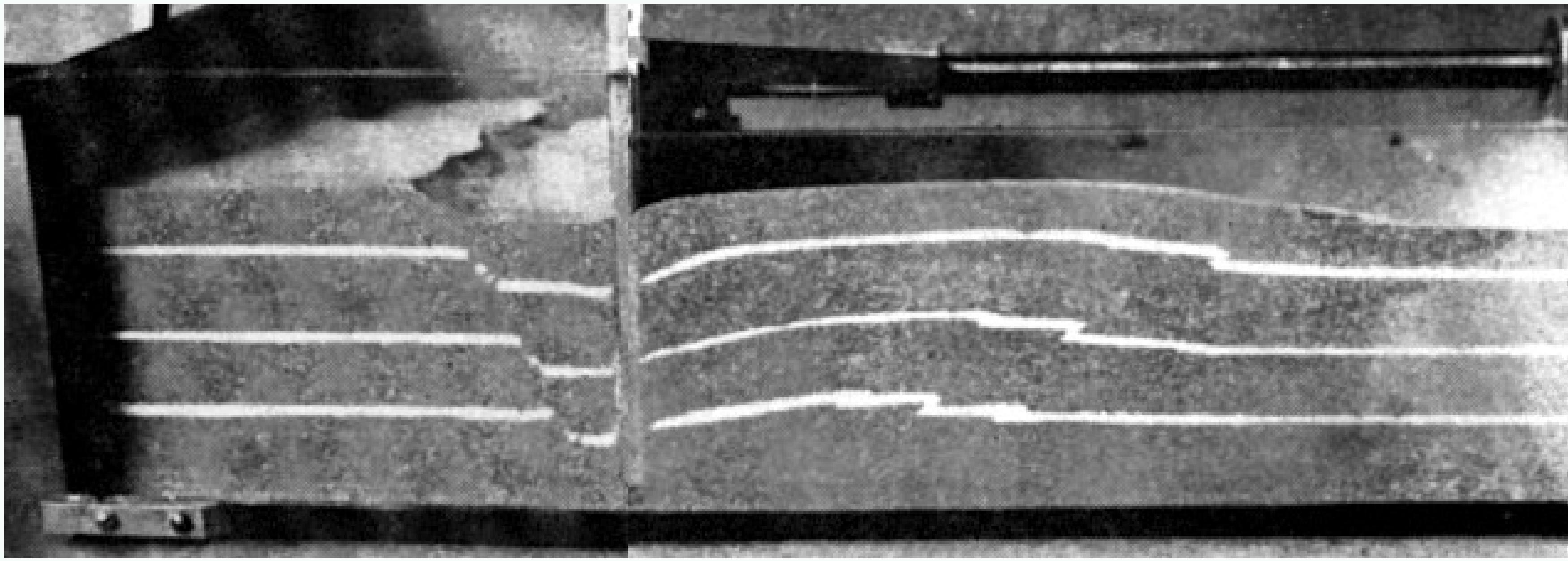
External Stress Boundary Conditions

$$P_c = \frac{\nu}{(1-\nu)}\left[P_{ob} - \alpha_v P_p\right] + \alpha_h P_p + \varepsilon_x E + \sigma_t$$

Handling Tectonic Stress

- Two ways
  1. a constant regional stress can be added to one (or both) horizontal stresses over some vertical extent
  2. assume some regional strain which then generates a different stress in each layer, according to its stiffness
     - allows component of stress proportional to Young's Modulus
     - shown to work effectively in many field cases

Regional Strain Produces Tectonic Stress

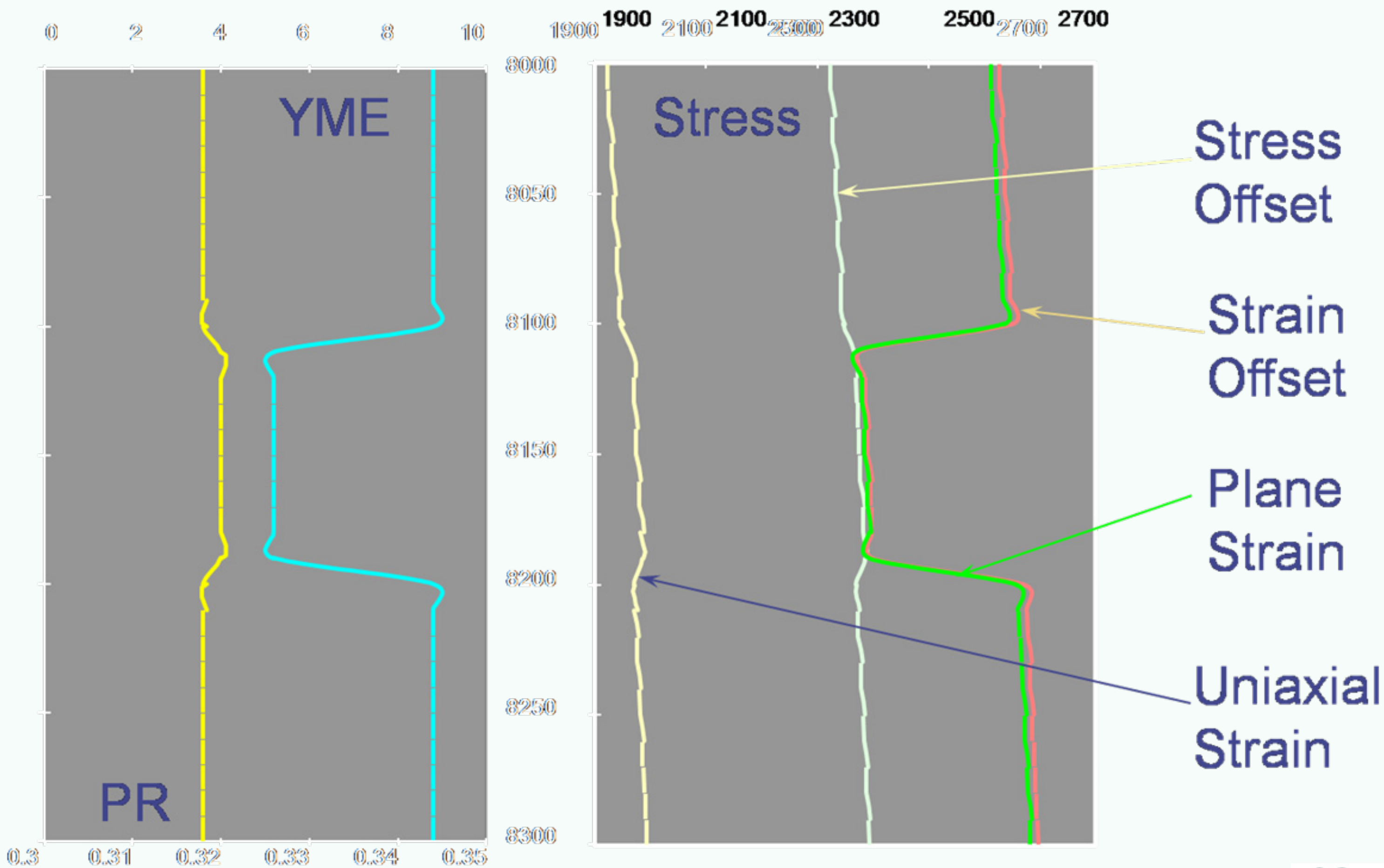


Tension

Regional Strain

Compression

Estimated Stresses Depend on the Model Used



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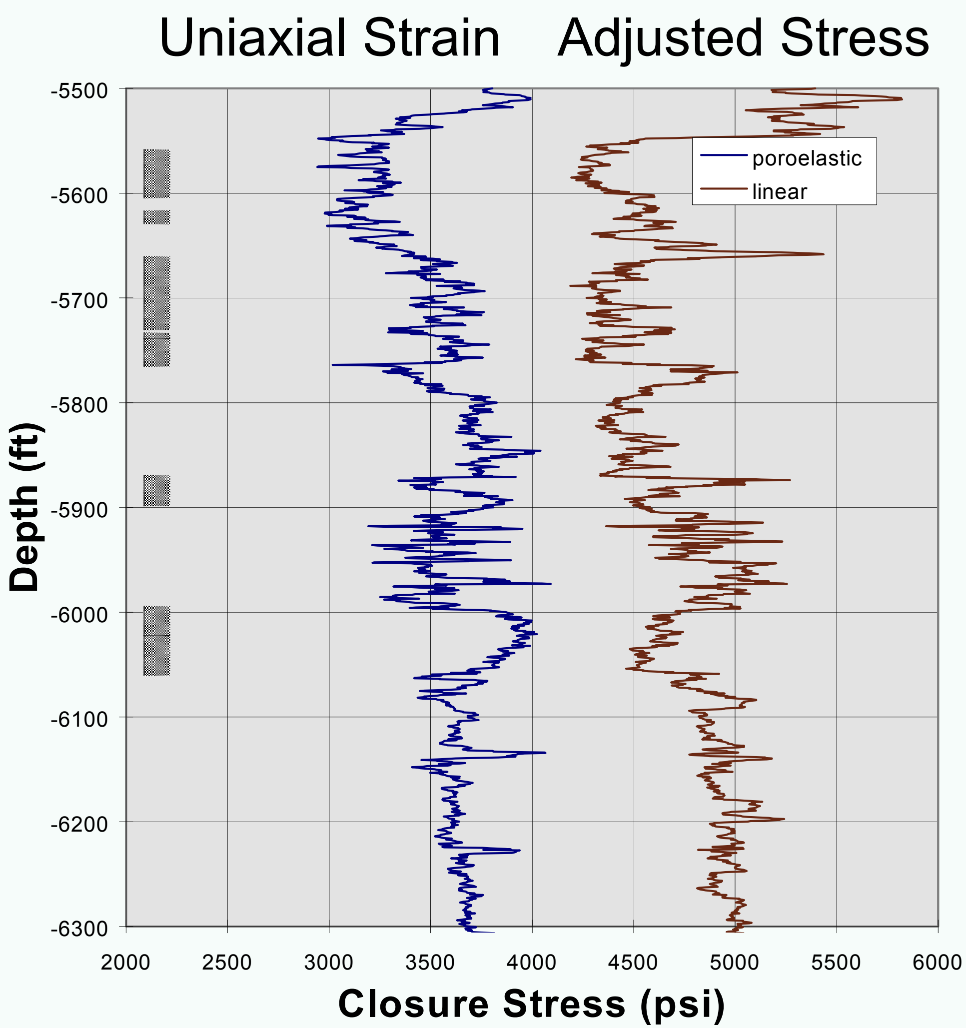
Stress Adjustments Through Tectonic Strain



Added 200 micro-strains regional strain to stress calcs to match observed closure stress of 4500 psi at 6050'

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GOHFER's Total Stress Equation

We have now examined the various parts of the total stress equation:

$$P_c = \frac{\nu}{(1-\nu)}\left[D_{tv}\gamma_{ob} - \alpha_v\left(D_{tv}\gamma_p + P_{off}\right)\right] + \alpha_h\left(D_{tv}\gamma_p + P_{off}\right) + \varepsilon_x E + \sigma_t$$

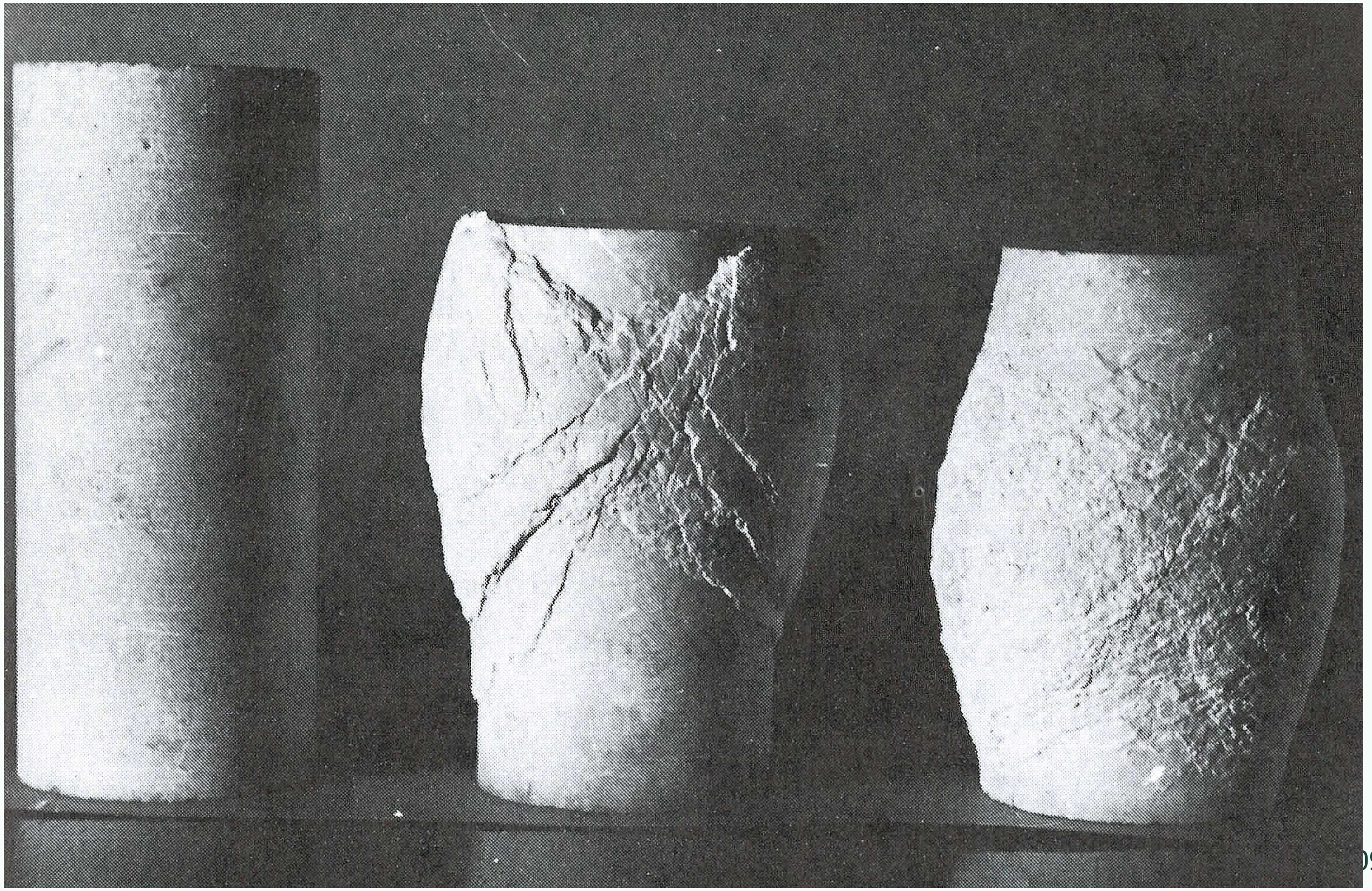
Other Height Containment Mechanisms

- Inelastic energy dissipation
  - shear failure
  - bed slip
  - natural fractures
  - plastic deformation

Need to re-examine classical LEFM models (Linear Elastic Fracture Mechanics)

Plastic Deformation of Rocks Under Confining Stress

Original Sample | **4000 psi Confining Stress** | **6500 psi Confining Stress**



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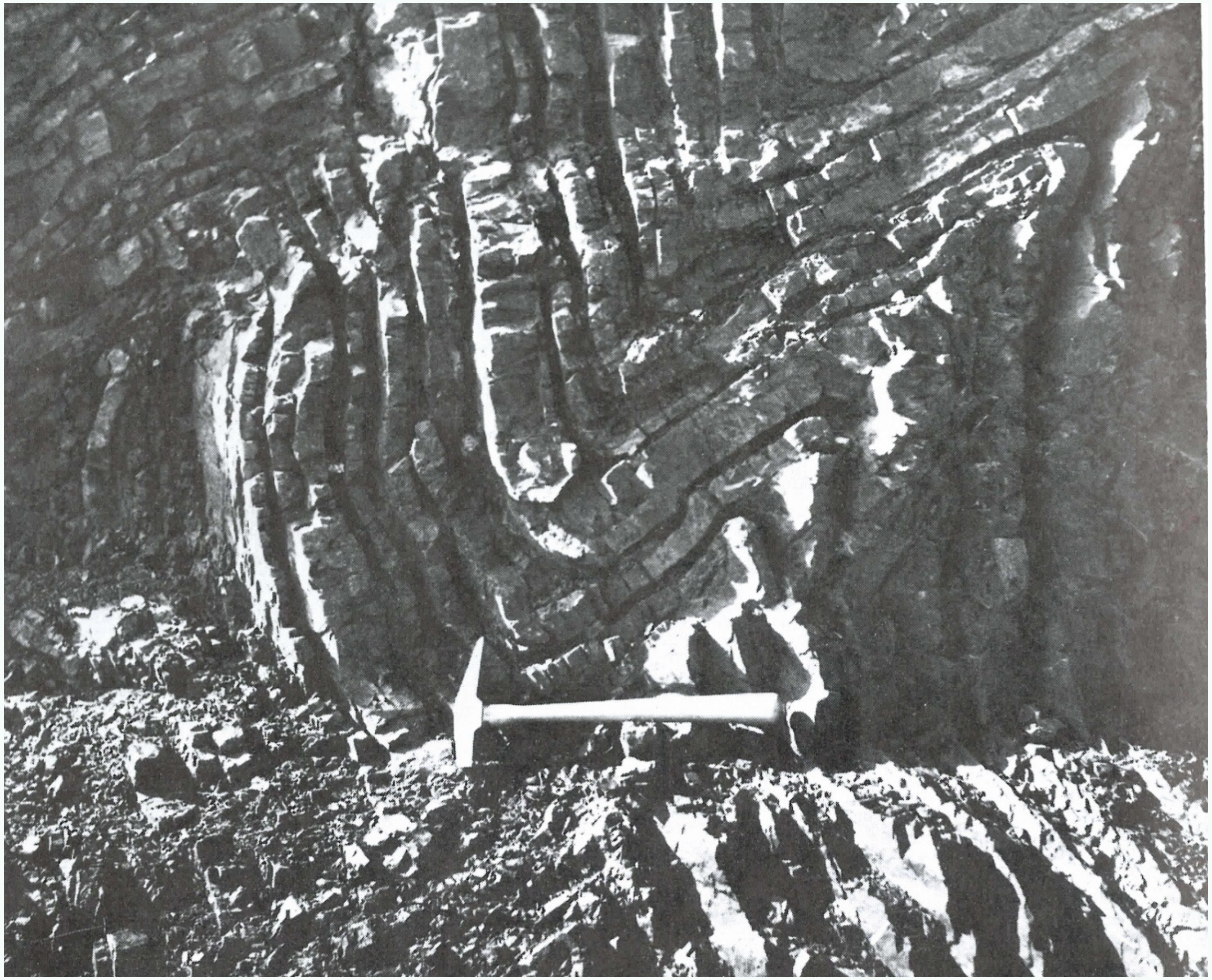
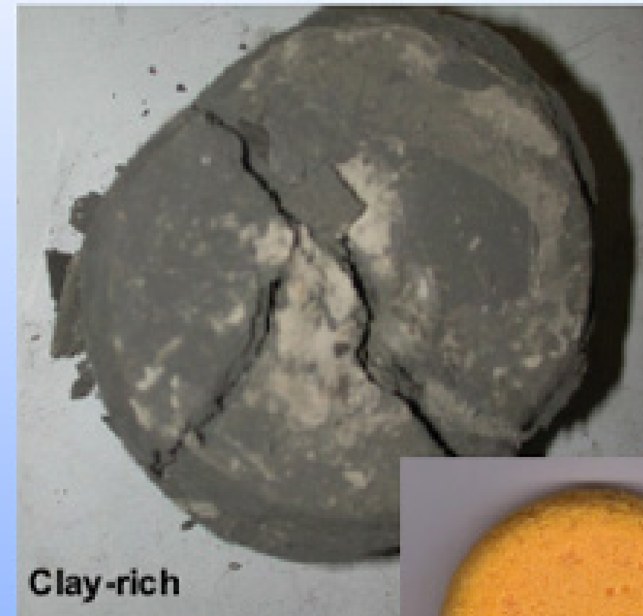
Rocks Behave Like Plastic Materials



Are All Shales the Same?

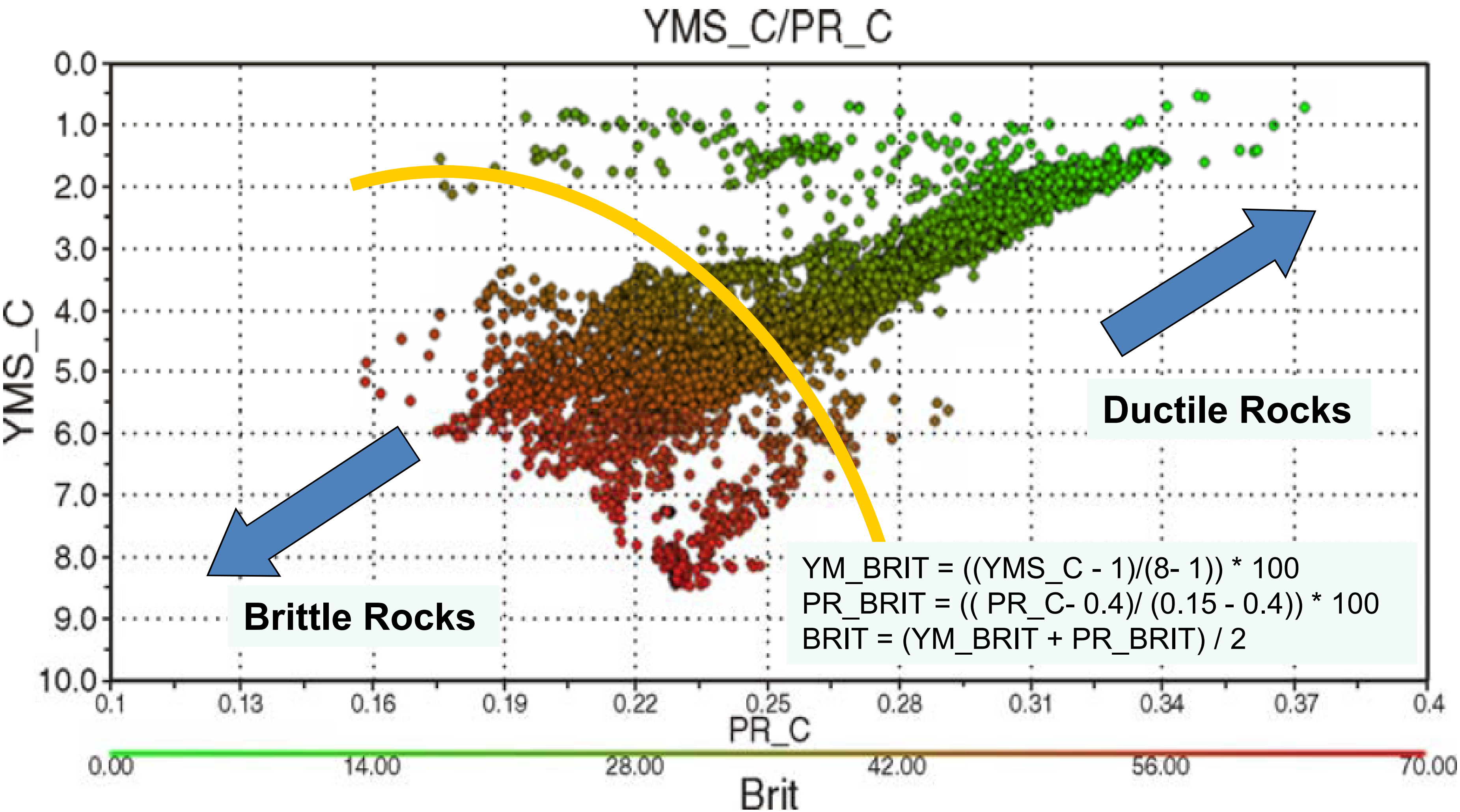
Brittle vs. Ductile Behavior

Barnett Shale



Upper Cretaceous WCSB

Definition of Brittleness Based on E (YMS_C) and ν (PR_C)

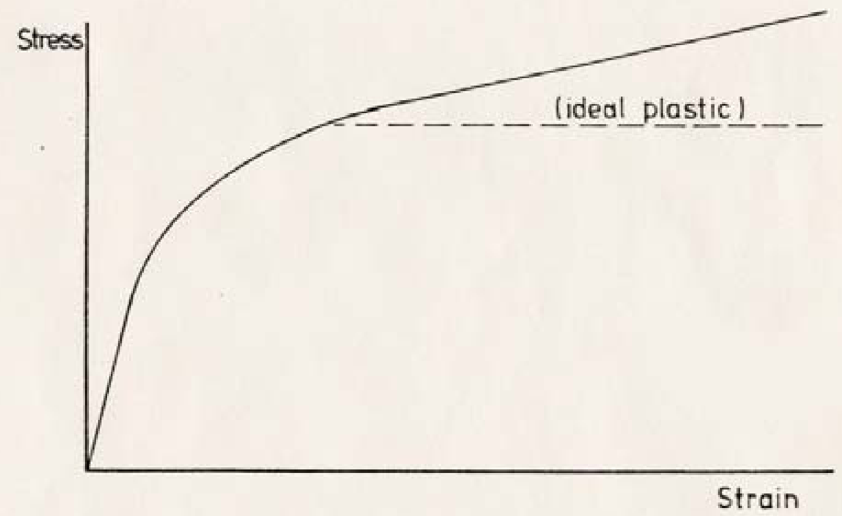


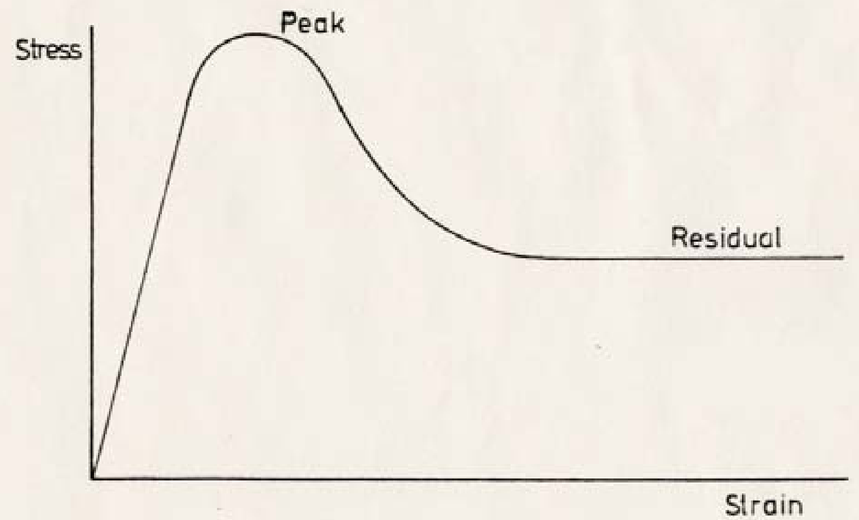
Proposed Fracture Stimulation Choices Based on Brittleness

Brittleness	Fluid System	Fracture Geometry	Fracture Width Closure Profile	Proppant Concentration	Fluid Volume	Proppant Volume
70%	Slick Water			Low	High	Low
60%	Slick Water					
50%	Hybrid					
40%	Linear					
30%	Foam					
20%	X-Linked					
10%	X-Linked			High	Low	High

Mullen, SPE 115258

Definition of Brittle-Ductile Failure

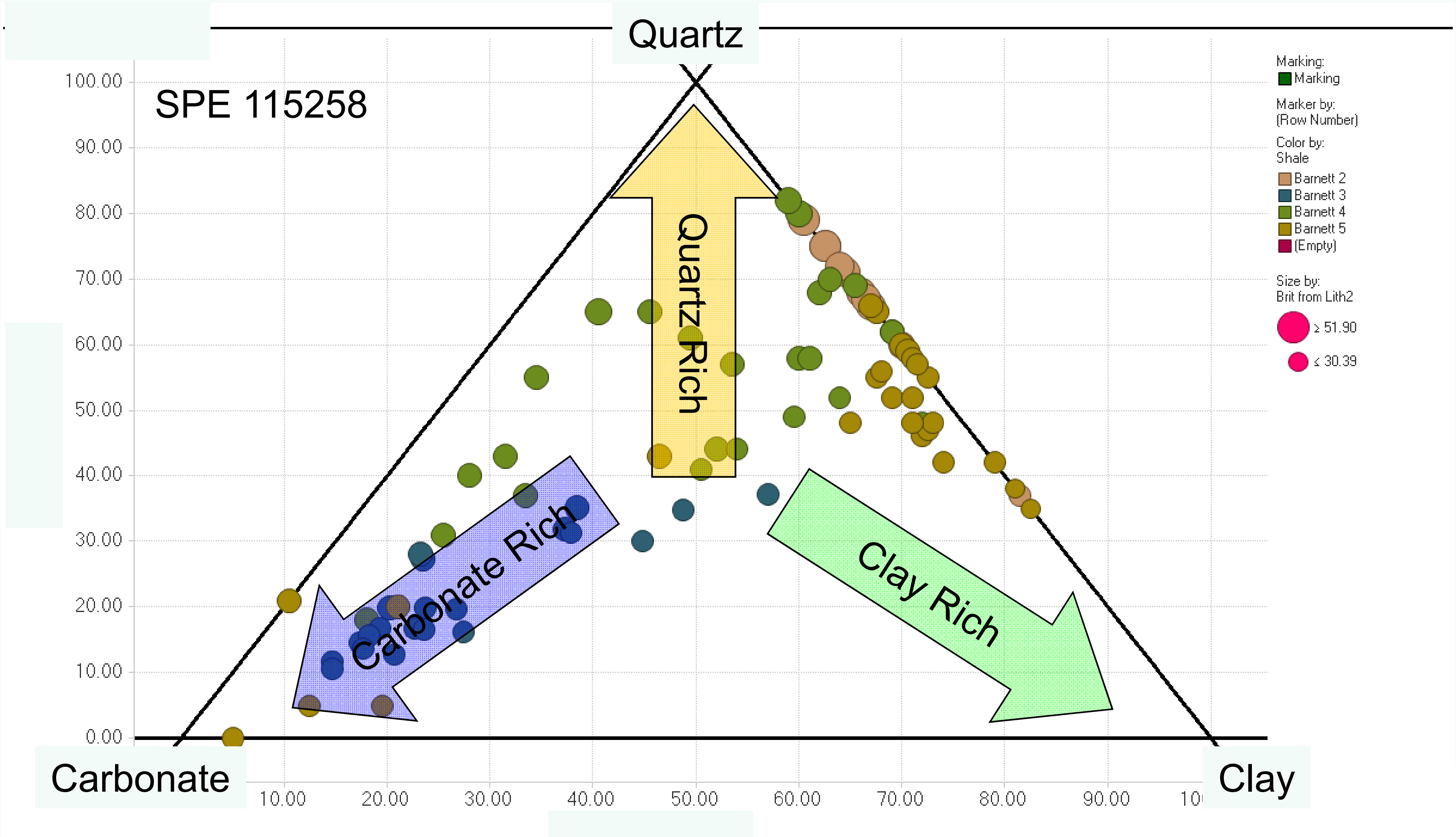




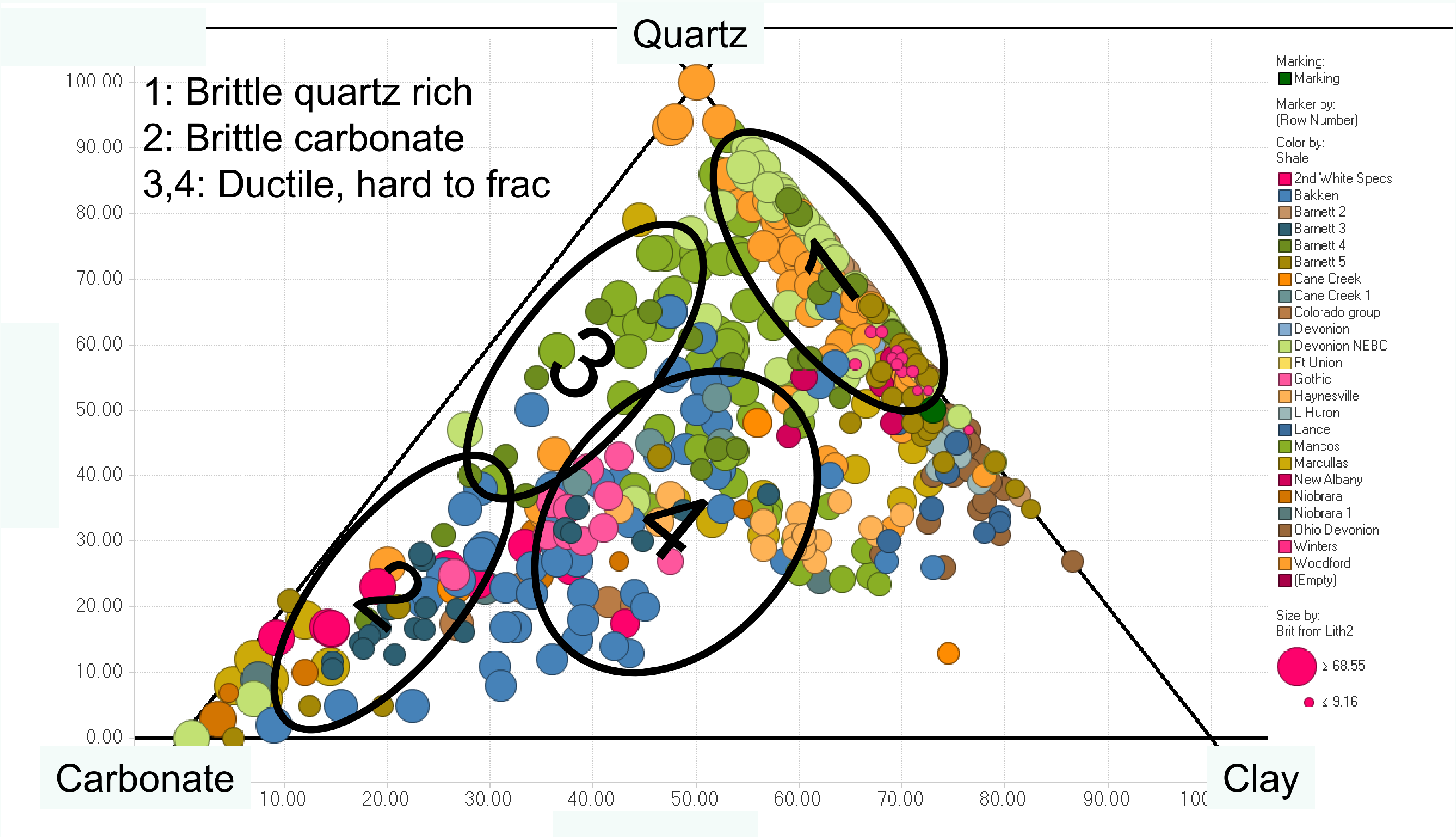
Quasi-plastic or strain-hardening

Brittle failure or strain-softening

Ternary Diagram of the mineralogy of four Barnett Shale Wells



Ternary Diagram of the mineralogy of all Shales in the North America Database



Plasticity and Creep:
Effects on Stress Estimates

- Apparent Poisson's Ratio approaches 0.5
- Horizontal stresses become nearly equal
- Horizontal stress can almost equal vertical stress
- Tendency for strong height containment in clay-rich, plastic sediments
- Possible blunting or fracture truncation

Lithologies Susceptible to Plastic Creep

- Coals
- Carbonates (at great depth)
- Gumbo Shales
- Evaporites
  - Halite
  - Anhydrite

Confirming Input Data Accuracy

- Need direct mapping of fracture growth
- Most data suggests that containment is much better than expected
- The stress model used is at least as important as the input data
- Elastic properties derived from sonic logs may not be the most useful
- Surrogate properties may give more predictive results
- Poroelasticity is important and may give a time and permeability dependence on apparent stress
- Assuming α_v(PHIE) and α_h=1 gives the largest stress contrast in most systems
- Often other containment mechanisms must be invoked (shear-slip and layered media)